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ABSTRACT

Part of a continuing study of application of communication satellites for helping to meet educational needs, this memorandum discusses operating frequencies for educational satellite services. Each of the factors affecting choice of transmission frequencies is identified and discussed in a separate section. Included among these factors are international radio regulations, with emphasis on frequency allocations, power-flux density restrictions, and the introduction of broadcasting-satellite systems; natural environmental effects, divided into those due to transionospheric propagation and those due to the earth's atmosphere; man-made environmental effects, in terms of various sharing limitations as well as the indigenous noise contribution to the overall system noise; hardware considerations, with an attempt to show the frequency dependence of system cost and performance; and interconnection and spectrum space considerations, covering the implications of educational telecommunication needs. The last section deals with various specific recommendations for educational interests in terms of frequency choice and related actions for domestic rule-making for incorporating the 1971 World Administrative Radio Conference (WARC) frequency allocations in the domestic frequency table. (Author/SH)

WASHINGTON UNIVERSITY

Memorandum No. 71-10 November, 1971

Operating Frequencies For Educational Satellite Services

Jai P. Singh

WASHINGTON UNIVERSITY / ST. LOUIS / MISSOURI 63130

PROGRAM ON APPLICATION OF COMMUNICATIONS SATELLITES
TO EDUCATIONAL DEVELOPMENT

WASHINGTON UNIVERSITY

Memorandum No. 71/10

November, 1971

OPERATING FREQUENCIES FOR EDUCATIONAL SATELLITE SERVICES

Jai P. Singh

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OPERATING FREQUENCIES FOR EDUCATIONAL SATELLITE SERVICES*

1. INTRODUCTION

This memorandum is a part of a continuing study of application of communication satellites for helping to meet U.S. educational needs. First, the factors affecting the choice of transmission frequencies are identified. These include international radio regulations, natural environment, man-made environment, hardware considerations, and interconnection and spectrum space considerations.

An analysis is then presented of international radio regulations with emphasis on 1963 EARC and 1971 WARC frequency allocations, power-flux density restrictions, and resolutions concerning introduction of Broadcasting-Satellite Systems. Natural-environmental effects have been divided into two categories: (1) those due to transionospheric propagation, and (2) those that can be credited to the earth's atmosphere and its constituents. The frequency dependence of the signal attenuation, signal distortion, and contributions to system noise temperature due to environmental effects are discussed and comparisons have been made for frequencies of interest. Next,man-made environmental effects have been examined in terms of various sharing limitations as well as the indigenous noise contribution to the overall system noise.

In the section on hardware considerations, an attempt has been made to show the frequency dependence of system cost and performance based on results in the published literature. The section on interconnection and spectrum space considerations deals with the implications of the special nature of educational telecommunication needs, and relates potential opportunities to the choice of transmission frequencies. The implications of the various alternatives have been discussed in view of the educational interconnection requirements.

The last section of this memorandum, the conclusions, deals with various specific recommendations for educational interests in terms of frequency choice and related actions for the forthcoming round of domestic rule-making for incorporating WARC allocations in the domestic frequency table. An Appendix has been added which describes the development of the U.S. position for WARC and compares the WARC allocations with those suggested by U.S.

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2. FACTORS AFFECTING THE CHOICE OF OPERATIONAL FREQUENCIES

2.1 Introduction

The choice of uplink (earth-to-space) and downlink (space-to-earth) frequencies for fixed-satellite and broadcasting-satellite services depends on many considerations. The most prominent of these are:

(a) International Radio Regulations

(b) Natural Environment

(c) Man-made Environment

(d) Hardware Considerations, and

(e) Interconnection and Spectrum Space Considerations.

It should be kept in mind that many of these considerations are not exclusive of each other. For example, the international allocations of frequencies are based to some extent upon the natural environment, state-of-the art of electronic hardware, and spectrum space requirements as well as the man-made environment (interference to and from services sharing the same spectrum, electromagnetic radiations from electrical machinery and automobile ignition, etc.).

2.2 International Radio Regulations

2.2.1 1963 Extraordinary Administrative Radio Conference (EARC)

The communication-satellite service* was established and frequency allocation provisions were effected internationally by the International Telecommunications Union (ITU) Extraordinary Administrative Radio Conference

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*The ITU recognizes two general classes of services: (1) the Radio Services, which include such services as fixed, mobile, broadcasting, radio location, radio astronomy, amateur, standard frequency, etc.; and (2) the Space Services, consisting of space research and communication-, broadcasting-, radio navigation, and meteorological-satellite services. A terrestrial service is any radio service other than a space service or radio astronomy. A "terrestrial" station is a station in a terrestrial service, while "earth" (including aircraft) and "space" stations are stations in a space service.

1971 World Administrative Radio Conference (WARC) just concluded, has renamed Communication-Satellite Service as Fixed-Satellite Service (see Section 2.2.2 and Appendix A). Fixed-Satellite Service is a space service for point-to-point communication between fixed earth stations via active/passive satellites. By the virtue of the altitude of the satellite, this service is also capable of distributing program material over a wide area for rebroadcast purposes.

to Allocate Frequency Bands for Space Radio Communication Purposes, Geneva, 1963. Before that, the entire spectrum below 40 GHz was allocated to terrestrial radio services; almost all the spectrum below 10 GHz was in use in terrestrial services. Different countries were using the different segments of this spectrum (below 10 GHz) in different ways and at the same time, technology was not advanced enough to permit the use of frequencies above 10 GHz if communication satellite services were to be implemented soon. It became necessary to make compromises between the demands of communication-satellite servcies and those of terrestrial services; to accept communication-satellite allocations shared with terrestrial services, with constraints on both and to resort to ITU regional allocations.

For the purposes of the allocations, the world has been divided into three regions as indicated in Figure 1. Region I consists of Europe, Africa, the Near East, and the U.S.S.R.; Region II consists of the Americas; and Region III the Middle and Far East, Malaysia, Australia, and Oceania. The ITU 1963 EARC allocated a total of 2,800 MHz spectrum space to the communication-satellite service in ITU Region I, 2,600 MHz in Region II, and 2675 MHz in Region III. Table 1 shows ITU 1963 EARC allocations for all the Regions. Primary services are printed in capital letters and secondary services in lower-case, the former being distinguished largely by having prior choice of frequencies and protection from interference from secondary services.

As is evident from Table 1, five frequency bands were allocated by the 1963 EARC. Two bands of 800 and 500 MHz width, respectively, in the 3400 to 4200 MHz and 7250 to 7750 MHz bands were made available for satellite-to-earth or "downlink", while three bands of 300, 500 and 500 MHz width, respectively, in the 4400-4700, 5925 to 6425 (for Region II) and 7900 to 8400 MHz bands were allocated to earth-to-satellite or "uplink". Exception was made for the passive communication-satellite service, which does not involve any frequency translation as well as any signal processing at the satellite, and which was to be accommodated in the 7250 to 7750 MHz band. Most of the allocations are shared with fixed and mobile services, and to some extent with radio location service in the 3400 to 4200 MHz and 5925 to 6425 MHz bands. Notably, two bands of 50 MHz width each were allocated by the EARC for exclusive communication-satellite use in the 7250 to 7300 MHz and 7925 to 8025 MHz bands.*

Of 2,600 MHz spectrum space allocated by the EARC for the communication-satellite service in Region II (the Americas), the United States was able to use only 2,000 MHz for communications satellites because of noncompatible use of 600 MHz for terrestrial purposes.[1] U.S. allocations exclude the 3400 to 3700 MHz portion of the 3400 to 4200 MHz downlink allocations as

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*1963 EARC also made certain allocations for space services below 3 GHz (see Appendix 14, Ref. 1), but most of them have a small bandwidth (usually less than 10 MHz), insufficient for our purposes. Only two bands (1540-1660 MHz and 2200-2290 MHz) have large enough widths to be of any interest to us but they are allocated to aeronautical radio-navigation (space development) and meteorological satellite service, respectively.

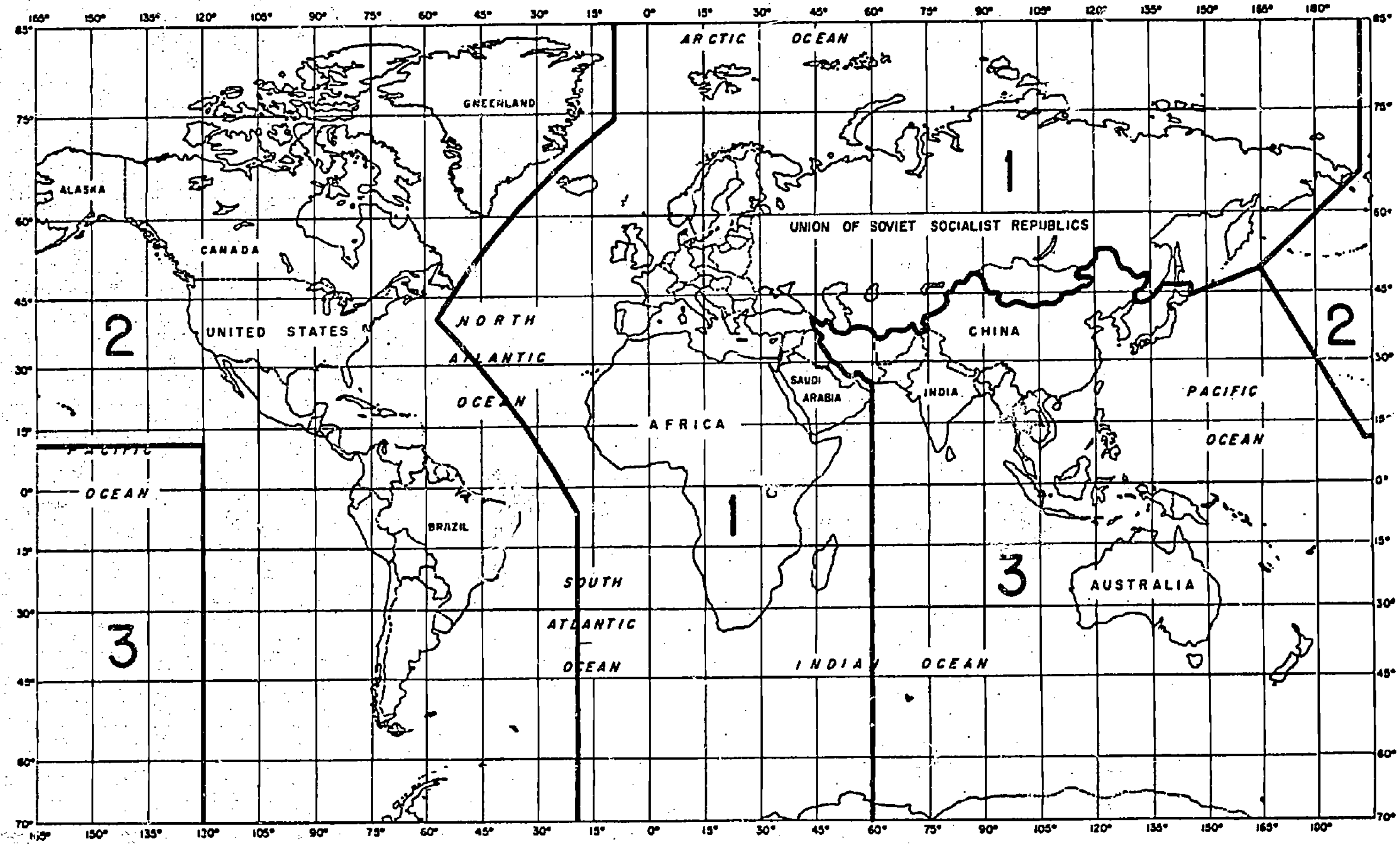

Fig. 1 —I. T. U. frequency allocation regions

TABLE 1

EARC COMMUNICATION SATELLITE FREQUENCY ALLOCATIONS (MHz)

	Region 1 Eurasia and Africa	Region 2 The Americas	Region 3 Australasia
satellite to earth	3400-2600 FIXED MOBILE COMMUNICATION-SATELLITE Radiolocation	3400-3500 RADIOLOCATION COMMUNICATION SATELLITE Amateur	
		3500-3700 FIXED MOBILE RADIOLOCATION COMMUNICATION-SATELLITE	3500-3700 RADIOLOCATION COMMUNICATION-SATELLITE Fixed Mobile
	3600-4200 FIXED COMMUNICATION-SATELLITE Mobile	3700-4200 FIXED MOBILE COMMUNICATION SATELLITE	
earth to satellite	4000-4700 FIXED MOBILE COMMUNICATION-SATELLITE		
earth to satellite	5725-5850 RADIOLOCATION COMMUNICATION-SATELLITE Amateur		
	5850-5925 FIXED MOBILE COMMUNICATION-SATELLITE		5850-5925 FIXED MOBILE COMMUNICATION-SATELLITE Radiolocation
	5925-6425 FIXED MOBILE COMMUNICATION-SATELLITE		
satellite to earth and passive	7250-7300 COMMUNICATION-SATELLITE		
	7300-7750 FIXED MOBILE COMMUNICATION-SATELLITE		
earth to satellite	7900-7975 FIXED MOBILE COMMUNICATION-SATELLITE		
	7975-8025 COMMUNICATION-SATELLITE		
	8025-8400 FIXED MOBILE COMMUNICATION-SATELLITE		

well as the entire 4400 to 4700 MHz uplink band. Table 2 shows the U.S. allocation provision. As reflected by footnote US91 to the Table of Frequency Allocations, the 4 and 6 GHz frequency bands were adopted for the commercial global communication-satellite system because the widespread development of microwave communication systems, primarily those belonging to the common carriers, in these bands had provided the hardware and technology for early establishment of a global system; also, from the viewpoint of available satellite effective isotropic radiated power (e.i.r.p.), a 4 GHz downlink was more attractive than the 7 GHz band. The 7 and 8 GHz bands were adopted for the U.S. government systems. According to the footnote US91, the ultimate disposition of all the frequency bands for communication-satellite service between government and non-government usage is deferred. However, for all practical purposes, the disposition is very much final. When the Federal Communications Commission, which has the sole authority over the administration of non-government frequency bands, initiated its domestic satellite inquiry, 4 and 6 GHz were the frequency bands suggested for the operational system(s). Here one cannot refrain from taking note of the fact that of 2000 MHz spectrum space for communication-satellite service that is allocated within the U.S., only 50 percent of it is available for nongovernmental purposes.

To permit the shared use of these frequency bands so that various competing services could co-exist without causing undue interference to each other, EARC also imposed certain restrictions in terms of effective radiated power (e.r.p.), antenna elevation angle, and power flux density at the earth's surface (see Table 2 footnotes) in addition to elaborate coordination procedures for siting earth-stations and new microwave relay terminals.

In two of the frequency bands allocated for earth-to-satellite transmission, the maximum e.r.p. of stations in fixed and mobile services is restricted to +55 dBW, and the power delivered to the antenna to +13 dBW (20 Watts). This includes all of the 5925-6425 MHz and a portion of the 7900-8400 MHz band (7900-7995 MHz).

The mean e.r.p. transmitted from an earth-station in the communication-satellite service in any direction in the horizontal plane is limited to +55 dBW in any 4 kHz band, except where site shielding and geographical separation permit an increase up to a maximum of +65 dBW in any 4 kHz band. Also the angel of earth-station antenna elevation for transmission to the satellite is restricted to a minimum of 3°. Except for the +65 dBW maximum, these limitations may be exceeded by agreement between the administrations (governments) concerned.[3]

The total satellite radiated power-flux-density (PFD) at the earth's surface is restricted to -130 dBW/m^2 for all angles of arrival for satellites using wide-band frequency or phase modulation and is to be limited, if necessary by suitable continuous modulation, to no more than -149 dBW/m^2 in any 4 kHz band. For other forms of modulation, the PFD is limited to -152 dBW/m^2/4 kHz for all angles of arrival. However, the Consultative Committee for International Radio (CCIR) of ITU has developed several proposed modifications of the original sharing criteria to take technological advances into account and provide a more balanced treatment

TABLE 2

U.S. ALLOCATION PROVISION

Frequency Band - MHz	
3700 - 4200	Non-Government Fixed (microwave) Communication Satellite (space to Earth) US91 1/
5925 - 6425	Non-Government Fixed (microwave) 2/ Communication Satellite (Earth to space) US91 3/ 4/
7250 - 7300	Communication Satellite (space to Earth) US91 1/
7300 - 7750	Government Fixed 2/ Government Mobile 2/ Communication Satellite (space to Earth) US91 1/
7900 - 7975	Government Fixed 2/ Government Mobile 2/ Communication Satellite (Earth to space) US91 3/ 4/
7975 - 8025	Communication Satellite (Earth to space) US91 3/
8025 - 8400	Government Fixed 2/ Government Mobile 2/ Communication Satellite (Earth to space) US91 3/ 4/

1/ Space station flux density at Earth's surface is limited by RR470-O and 470-P to not more than -152 dBW/m^2 in any 4 kHz band for any system of modulation and all angles of arrival. (The CCIR has recommended $-152 + \theta/15$ dBW/m^2).

2/ Terrestrial stations are limited to an effective radiated power of +55 dBW and not to exceed +13 dBW into the antenna by RR470-B and 470-C in 5925-6425 and 7900-8100 MHz bands.

3/ Earth station effective radiated power is limited by RR470-G to +55 dBW in any 4 kHz band in the horizontal plane and to +65 dBW in any 4 kHz band at any vertical angle, except as modified by RR470-H and 470-I; and minimum angle of elevation of 3°.

4/ The U.S. limits the EIRP in the horizontal plane to +45 dBW in any 4 kHz band in the band 5925-6425 MHz or +55 dBW in any 4 kHz band in the bands 7900-7975 and 8025-8400 MHz; and normally a minimum elevation angle of 5°.

US91 The ultimate disposition of this band in the communication-satellite service, as between G and NG, is deferred. In the meanwhile, the NG may exploit the 4 and 6 GHz bands, and the G may exploit the 7 and 8 GHz bands for communication-satellite service systems intended to become operational...

of satellite and terrestrial systems. First, the CCIR recommends removal of the total flux limitation of $-130\ dBW/m^2$, since flux density per unit bandwidth is the only effective measure of interference potential. Next, it has proposed that the $-149\ dBW/m^2/4$ kHz PDF limitation be replaced by a new one which recognizes that satellites appearing at high elevation angles cannot couple directly into terrestrial radio relay system antennae but only at reduced efficiency through antenna sidelobes. The limit proposed is $(-152 + \phi/15)\ dBW/m^2$ per 4 kHz bandwidth, where ϕ is the satellite elevation angle from the point in question.

These limitations have certain implications on the system design in terms of the system cost and complexity; implications which will be discussed towards the end of this section along with those arising from the recently held World Administrative Radio Conference (WARC).

2.2.2 1971 World Administrative Radio Conference (WARC)

Some five years after the time EARC was convened in Geneva, the ITU at the 23rd session of its Administrative Council, also held in Geneva, May 11-31, 1968, adopted the following resolutions[5]:

> "To recommend to administrators that a World Administrative Radio Conference shall be convened during the latter part of 1970 or early 1971. . .with an agenda to include in particular the following items:
>
> (3) to consider and provide as far as possible, additional radio frequency allocations for the space radio services;
>
> (5) to revise and supplement as appropriate the existing technical criteria for frequency sharing between space and terrestrial systems and establish criteria for sharing between satellite systems; . . . ."

This recommendation resulted in the recently held World Administrative Radio Conference (June-July 1971, Geneva) that has allocated an additional 37.4 GHz total spectrum space (extending up to 275 GHz) for fixed-satellite as well as broadcast satellite services.* WARC has allocated certain

*Broadcasting-Satellite Service (BSS) is a space service in which signals transmitted or retransmitted by space stations (satellites) are intended for direct reception by the general public. BSS can be divided into two distinct categories: (1) systems that allow individual reception; and (2) systems which are designed for community reception. In the case of individual reception or direct-to-home type BSS systems, the strength of the emissions from the satellite is strong enough to allow reception through simple domestic installations. Community reception-type BSS systems are designed for reception by receiving equipment which in some cases may be large installations and have large antennae and are intended (1) either for group viewing and/or listening, or (2) for local distribution of signals by cable, including CATV installations, or (3) in some cases for rebroadcasting to limited areas.

portions of the spectrum for the exclusive use of fixed-satellite (previousl known as communication-satellite service) and broadcast-satellite services (see Table 3) as well as certain shared allocations.

WARC not only maintained the shared allocations below 10 GHz for fixed satellite service but also allocated three additional frequency bands below 10 GHz for fixed-satellite as well as broadcasting-satellite services: 620-790 MHz UHF-TV band for Broadcasting-Satellite Service on a footnote basis; use of 2500-2535 and 2655-2690 MHz bands for fixed-satellite service; use of 2500-2690 MHz band for Broadcasting-Satellite Service (limited to domestic and regional systems) for community-reception; and the use of 6625-7125 MHz band on a secondary basis for space-to-earth transmission in the fixed-satellite service.

The other important allocations, both for fixed-satellite and broadcasting-satellite services, were made in the X- and Ku-Bands. WARC allocated the 10.95-11.2 GHz and 11.45-11.7 GHz bands to fixed-satellite ser vice for space-to-earth transmissions (on a shared basis with terrestrial fixed and mobile services). Most importantly, it allocated the 11.7-12.2 GHz band in Region II to fixed-satellite and broadcasting-satellite services on a coequal basis to be shared with terrestrial broadcasting, fixed, and mobile (except aeronautical) services. WARC has ruled that terrestrial radio-communication services in the 11.7-12.2 GHz band shall be introduced only after the elaboration and approval of plans for the space radio-communication services, so as to ensure compatibility between the uses that each country decides for this band. However, WARC limited the use of the band 11.7-12.2 GHz by the broadcasting-satellite and fixed-satellite services to domestic systems and made the use of these frequencies subject to previous agreement among administrations concerned and those having services, operating in accordance with Table 3, which may be affected.

WARC also placed limits on maximum satellite radiated power-flux density (PFD) reaching the earth's surface. For S-band fixed-satellite downlink allocation (2.500-2.535 GHz), PFD is not to exceed -154 dBW/m^2/4 kHz escalating to -144 dBW/m^2/4 kHz between 5 and 25 degrees (elevation). For the broadcasting-satellite service in the S-band (2.500-2.690 GHz), PFD is limited to -152 dBW/m^2/4 kHz escalating to -137 dBW/m^2/4 kHz between 5 to 25 degrees (see Figure 2). 6.625-7.125 GHz fixed-satellite service downlink PFD is restricted to -152 dBW/m^2/4 kHz escalating to -142 dBW/m^2/4 kHz between 5 and 25 degrees. For 10.95-11.2 GHz and 11.45-11.7 GHz fixed-satellite service downlinks, WARC has recommended the maximum PFD as -150 dBW/m^2/4 kHz escalating to-140 dBW/m^2/4 kHz between 5 and 25 degrees. Figure 2 shows PFD limits for the various downlink frequencies (fixed-satellite and broadcasting-satellite services) as a function of the elevation angle (ϕ). For the purposes of comparison, it also translates the PFD limits to satellite transponder e.r.p. on the assumption of a 40 MHz transponder and signal bandwidth. For translating PFD to satellite transponder e.r.p. for use in Figure 2, we simply assumed a -162.1 dB ($1/4\pi r^2$) loss, no propagation medium attenuation (the latter being frequency dependent) and a zero value Range function ($R(\phi)$). In real situations, the e.r.p. limit (expressed in dBW) would not be a

Table 3

WARC COMMUNICATION SATELLITE FREQUENCY ALLOCATIONS [MHz]

Region I Eurasia and Africa	Region II The Americas	Region III Australias
620 - 790 Broadcasting Satellite [Footnote]		
2500 - 2690 BROADCASTING SATELLITE* [Shared]	2500 - 2535 FIXED-SATELLITE (Space-to-Earth) BROADCASTING SATELLITE* [Shared]	
	2535 - 2655 BROADCASTING SATELLITE* [Shared]	
	2655 - 2690 FIXED-SATELLITE (Earth-to-Space) BROADCASTING SATELLITE* [Shared]	
	6625 - 7125 Fixed-Satellite (Space-to-Earth) [Secondary Basis] Brazil, Canada, & USA	
10950 - 11200 FIXED-SATELLITE [Shared] (Space-to-Earth & Earth-to-Space)	10950 - 11200 FIXED-SATELLITE [Shared] (Space-to-Earth)	
11450 - 11700 FIXED-SATELLITE [Shared] (Space-to-Earth)		
11700 - 12500 BROADCASTING SATELLITE [Shared]	11700 - 12200 FIXED-SATELLITE (Space-to-Earth) BROADCASTING SATELLITE [Shared]	11700 - 12200 BROADCASTING SATELLITE [Shared]
12500 - 12750 FIXED-SATELLITE[Shared] (Space-to-Earth & Earth-to-Space)	12500 - 12750 FIXED-SATELLITE [Shared] (Earth-to-Space)	
1400 - 14500 FIXED-SATELLITE [Shared] (Earth-to-Space)		
11700 - 19700 FIXED-SATELLITE [Shared] (Space-to-Earth)		
19700 - 21200 FIXED-SATELLITE (Space-to-Earth)		
22500 - 23000 BROADCASTING SATELLITE [Shared]		
27500 - 29500 FIXED-SATELLITE [Shared] (Earth-to-Space)		
29500 - 31000 FIXED-SATELLITE (Earth-to-Space)		
40000 - 41000 FIXED-SATELLITE (Space-to-Earth)		
4100 - 4300 BROADCASTING SATELLITE		
50000 - 51000 FIXED-SATELLITE (Earth-to-Space)		
84000 - 86000 BROADCASTING SATELLITE		
92000 - 95000 FIXED-SATELLITE (Earth-to-Space)		
102000 - 105000 FIXED-SATELLITE (Space-to-Earth)		
140000 - 142000 FIXED-SATELLITE (Earth-to-Space)		
150000 - 152000 FIXED-SATELLITE (Space-to-Earth)		
220000 - 230000 FIXED-SATELLITE (Transmission Direction Unspecified)		
265000 - 275000 FIXED-SATELLITE (Transmission Direction Unspecified)		

*For Community Reception Only.

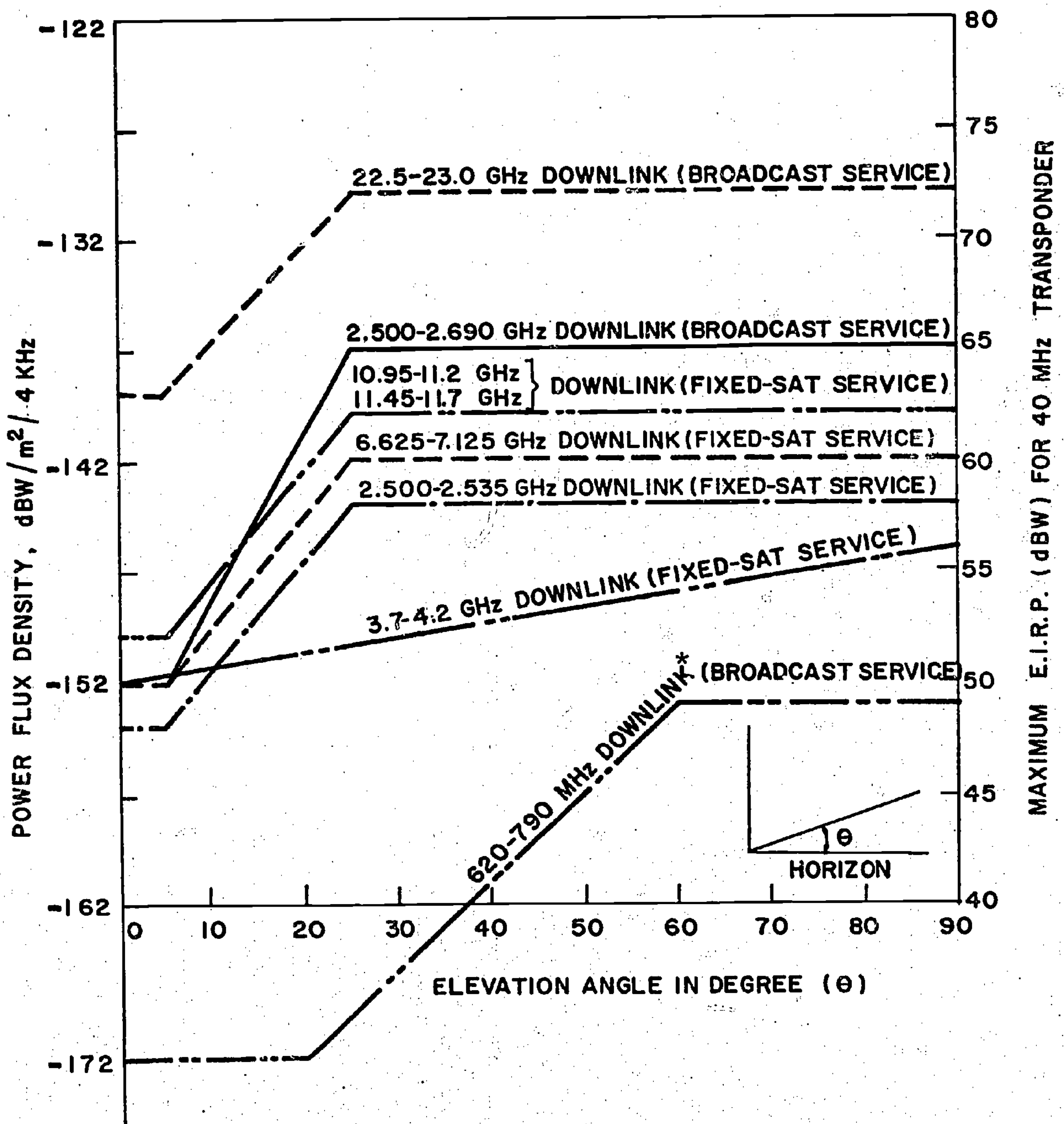

FIGURE 2. MAXIMUM E.I.R.P./ POWER FLUX DENSITY RECOMMENDED BY WARC/CCIR FOR VARIOUS DOWNLINKS

*Limit Not To Be Exceeded Within The Territories of Other Administrations Without The Consent Of Those Administrations.

straight-line function of the elevation angle (ϕ) because $R(\phi)$ is dependent on the elevation angle and assumes values in the range of $0 < R(\phi) < 1.0$ dB for $0 < \phi < 70$. In addition, e.r.p. limits for higher downlink frequencies would be higher than those that are shown in Figure 2 because higher frequencies suffer more from the propagation medium losses.* No PFD limitations are shown for the 11.7-12.2 GHz Fixed-Satellite and Broadcast-Satellite Services because WARC resolutions do not contain any.

In concluding this section, we would like to draw the reader's attention to Resolution No. Spa F of WARC which calls for the establishment of Broadcasting-Satellite Services after a World Administrative Conference and/or regional administrative conferences in which all the administrations concerned and the administrations whose services are likely to be affected are to participate. However, as yet no date for these planning conferences is fixed and no one expects them to be held prior to 1973. Fortunately, WARC has also passed a resolution (Spa G) that outlines procedures for establishing Broadcasting Satellites prior to the entry into force of agreement and the development of associated plans for the Broadcasting-Satellite Service that are to be developed through conferences proposed under resolution Spa F. Though resolution Spa G outlines procedures for bringing into use Broadcasting Space Stations (Satellites) prior to the planning conference(s), it also advises administrations to avoid, as far as possible, proliferation of broadcasting space stations before world wide plans have been developed. Resolution Spa G essentially outlines an entry procedure through coordination with other administrations whose services may be affected by BSS, an announcement of the technical characteristics of the proposed satellite which are necessary to assess the risk of interference to a terrestrial Radiocommunication service, and necessary notifications to the International Frequency Registration Board (IFRB). Any unfavorable comments from IFRB upon the proposed satellite do not seem to have any binding effect on the user administration other than the fact that the service would not have any legality and the administration concerned would lose any rights to complaints regarding interference from any future service legally registered with IFRB. However, if a particular service has been in operation for 120 days and no interference complaints are received by IFRB, IFRB shall record the assignment in the master register. When harmful interference to other services in the territories of other administrations are caused and the services in the territories of other administrations are caused and the services there have an earlier entry in the master register of IFRB, the administration operating Broadcasting Satellite Space Station shall be asked to eliminate the said harmful interference.

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*At the earth's surface the flux density of satellite transmission can be expressed by[6]

$$H_{\text{dBW/m}^2\text{/4 kHz}} = -162.1 + \text{e.r.p.}_{(\text{dBW})} - L_p\ (\text{dB}) - R(\phi) - 10 \log (B/4)$$

where, L_p = attenuation in the propagation medium, dB

$R(\phi)$ = range function, dB

B = Transponder Bandwidth (in kHz)

It should also be noted that the sharing criteria defined by WARC are not final in the exact sense. Over the period of the next couple of years, one may expect some changes (generally favorable to space services) through International Radio Consultative Committee (CCIR) study group recommendations. As a final note, we would like to remind readers of this memorandum that the changes made by WARC are scheduled to enter into force January 1, 1973. Before the United States is bound by these changes, the changes would have to be signed by the President with the advice and consent of the Senate because the Radio Regulations comprise a treaty.

3. NATURAL-ENVIRONMENTAL EFFECTS

There are several frequency-dependent natural-environmental phenomenon that affect the choice of the frequencies for earth-space and space-earth communications. Effects produced by these environmental phenomenon can be classified into two broad categories: (1) those that are related to the propagation of the electromagnetic wave such as attenuation, wave distortion, and polarization-plane rotation; and (2) those that contribute to the overall system noise. However, some of these environmental effects are not separable into two distinct and mutually exclusive categories, e.g., atmospheric attenuation is accompanied by a change in the system noise temperature.

Environmental effects influencing the choice of operational frequencies for space communications have been studied and discussed in the literature [3,11-19]. However, for the sake of continuity and completeness we shall discuss them and their implications briefly.

3.1 Propagation Considerations

Propagation effects fall into two categories: (1) those due to transionospheric propagation, and (2) those that can be credited to the earth's atmosphere and its constituents.

3.1.1 Transionospheric Propagation

Ionospheric propagation effects include absorption, scintillation, Faraday rotation, and phase dispersion. Absorptive losses in the ionosphere are attributable to the transfer of energy from the propagating electromagnetic wave to the motion of the electrons in ionosphere. Absorptive losses are significant at frequencies only above the critical frequency and in general can be neglected. The critical frequency is the frequency below which the ionosphere is opaque to the RF spectrum. Observations made on the ionosphere have shown that the critical frequency exhibits diurnal, seasonal, and sporadic variations between 5 and 80 MHz. Thus for most practical purposes, in the frequency range that we are interested in, ionospheric absorption can be neglected. The UHF broadcasting-satellite allocation is the only one which would be affected by this phenomenon. For zenithal propagation paths, one could expect some 0.05-0.1 dB absorption in the 620-790 MHz BSS band.* For UHF waves arriving at low angle above the horizon and during sunspot maxima, the absorption may peak up to 4 dB.

A radio wave passing through the ionosphere is scattered by irregularities in the electron density distribution. The scatter results in a redistribution of the amplitude of the radio wave in a manner similar to the effect

*Ionospheric absorption is approximately proportional to the square of the inverted frequency. During a sunspot maximum, attenuation peaks up to 23 dB at 100 MHz radiation arriving at zenith.

of a diffraction grating, and also causes irregular fluctuations in the apparent position of a radio source viewed through the ionosphere. These processes are usually described as amplitude and angular scintillations.[21] Amplitude scintillations appear as fairly rapid and irregular variations in the recorded signal strength. Scintillations are most pronounced in the polar region and in the equatorial regions. In the polar regions, the zone of activity tends to be coincident with that of auroral activities. In the equatorial regions, the activity is to a large extent confined to a region of about $\pm$ 15° from the geometric equator.

Some of the earlier studies of the phenomenon indicate an inverse square frequency dependence of scintillation amplitude. For this reason, shifting of satellite transmission to higher frequencies has been used to alleviate the scintillation problem and until recently, the UHF band was the only satellite transmission band (communication-satellite as well as fixed-satellite) credited with small scintillations (few percent during strong disturbances). However, recent studies indicate that frequency dependence may not be strictly $1/f^2$ dependence, but may at times shift towards a $1/f$ law. In a recent study, Pope and Fritz[14] observed small but significant scintillations at S-band frequencies in the polar region that are caused by ionospheric characteristics similar to those causing scintillations at lower frequencies (VHF). They also confirmed that scintillations observed in the S-band were stronger than that would be predicted from the $1/f^2$ law. This means that for Alaska, S-band downlinks (2500-2690 MHz) would have to be provided with a link margin fraction of a dB more than that which would have been necessary in absence of scintillations.

Another major ionospheric effect is Faraday rotation, which causes the plane of polarization of an electromagnetic wave travelling through the ionosphere to change its orientation relative to the antenna from which it was transmitted, thereby causing an uncertainty as to the polarization of the wave to be received. As a result, unless certain precautions are taken, the desired signal may be completely lost. Faraday rotation effect is dominant at frequencies below S-band. Above 3,000 MHz, Faraday rotation effect may be neglected. However, below that frequency there is a possibility of losing from 3 dB to the entire signal, depending upon the polarization of the transmitting and receiving antenna. When transmitter and receiver both employ linear-polarization at frequencies below 3,000 MHz, there is a possibility that the signal may be completely lost. One is forced to use circular-linear polarization combination (circular at the satellite transponder and linear at the receive terminals) at UHF and S-band frequencies (620-790 MHz and 2500-2690 MHz) and suffer a 3 dB signal loss in the process. It should be recognized that circular polarization is expensive to implement relative to linear polarization because it is created by combining equal magnitudes of vertically and horizontally polarized waves, with the phase of one exactly 90° ahead or behind the other. When one is contemplating a large number of small earth-stations, as the case may be in 620-790 MHz and 2500-2690 MHz band, circular-circular combination would be excessively expensive.

The principal ionospheric effect of concern is the nonlinear variation of the refractive index with frequency which causes a dispersion. As a result, signal components of the various frequencies experience differing phase shifts which can result in significant distortions of the composite signal shape for wide-band signals. For pulse transmissions, the dispersive effect tends to spread out the pulse in time and produce modifications in the wave shape.[17] Furthermore, since the total delay of the signal in passing through the ionosphere is frequency-dependent, the communication system may be confronted with the presence of signals in several frequency channels at a specified time. These effects act to limit the communication capability of the system by restricting the maximum permissible bandwidth, or shortest pulse length. Sollfrey[17] has analyzed the transionospheric propagation of pulse signals and has concluded that the shortest acceptable pulse-width which may be employed in a pulsed communication system between earth and a satellite is approximately

$$T(\text{nsec}) = 4\ I^{1/2}\ [f(\text{GHz})]^{-3/2} \qquad \ldots(1)$$

where I is the number of electrons per square meter along the path in units of 10^6 and f is the frequency of operation. Clearly, the ionospheric dispersion effects on the minimum permissible pulse-width varies with $f^{-3/2}$. In practice, I is between 6 and 240, so $I^{1/2}$ is between 2.5 and 16. Thus, at 1 GHz, the shortest possible pulse-width ranges from 10 nsec (solar minimum, night) to about 60 nsec (solar maximum, winter day). At 5 GHz, these become 1 and 6 nsec, permitting very high data rates.

An important ionospheric effect on pulsed as well as analog signal transmission is related to the overall displacement of the frequencies causing group time delay distortion. The group time delay t_g may be given in terms of the parameter I as

$$t_g\ (\mu\text{sec}) = [4/3] \times 10^3\ I/f^2_{\text{MHz}} \qquad \ldots(2)$$

The parameter I, which is proportional to the number of electrons along the path from transmitter to receiver, should be multiplied by the secant of the zenith angle of this path. For ground-stations in temperate latitudes and satellites in geostationary equatorial orbit, this factor is typically between 2 and 3.[17] If I = 240, the group delay at 1000 MHz is 0.32 μsec, while at 1080 MHz it is 0.274 μsec. Thus, if a raised cosine pulse of width 0.05 μsec were transmitted at 1000 MHz, immediately followed by a 0.05 μsec pulse at 1080 MHz, the two pulses would arrive at the receiver almost simultaneously. Each distorted pulse can put appreciable energy into the receiver designed to accept the other.

Bedrosian[13] has presented a rigorous mathematical analysis of the transionospheric propagation of wideband FM signals (TV relay as well as Frequency Division Multiplex telephony) based on spectral analysis. He has derived expressions for Signal-to-Cross Talk ratio for the poorest telephony channel (topmost on the FDM baseband) and Signal-to-Distortion ratio (SDR) in the video baseband. According to Bedrosian[13], minimum Signal-to-Cross Talk Ratio is given by

$$SCR_{min} = 1.401 \times 10^{12} \frac{f_0^6}{D^2\ B^2\ N_T^2} \quad \ldots(3)$$

where, N_T is the electron density (electrons/m^2), f_0 is the carrier frequency in Hz, D is the rms frequency deviation of the FM signal (in Hz), and B is the highest frequency in the FDM multiplexed baseband (in Hz). N_T assumes values in the range 10^{17}-10^{18} depending upon the time of the day, the season, the position in the solar cycle, and the geographical location. The sixth power dependence on the carrier frequency clearly dominates and dictates use of as high a carrier frequency as possible for a given baseband signal and RF bandwidth. From the above given expression, one can see that ionospheric dispersion will not cause significant intermodulation distortion in a typical wide-band FDM-FM signal at frequencies of interest except under the most severe, and therefore generally infrequent, conditions. For example, for f_0 of 4 GHz, D = 20 MHz, and a 960 channel baseband (B = 4.028 MHz) and a worst-case ionospheric path with $N_T = 10^{19}$ electrons/m , SCR_{min} = 39.5 dB.

According to Bedrosian[13], the Signal-to-Distortion Noise Ratio (SDR) in the TV baseband can be approximated by

$$SDR = [12\ f_c^4\ /5\ D^2\ B^2] \quad \ldots(4)$$

where, as in the previous equation for Signal-to-Cross Talk ratio in the highest channel of the FDM baseband, D is the rms frequency deviation of the FM TV signal, and B is the baseband width. Parameter f_c has the units of frequency (Hz) and is generally known as "Characteristic Frequency" of the ionosphere at a particular carrier frequency. f_c is a function of the electron density integrated along the propagation path and the carrier frequency (f_0). f_c can be approximated by the following expression.

$$f_c = 1.088 \times 10^3\ [f_0^{3/2}\ /\ N_T^{1/2}] \quad \text{Hz} \quad \ldots(5)$$

Substituting the expression for f_c in the expression for SDR, one gets an expression for SDR in terms of carrier frequency (f_0), electron density (N_T), rms frequency deviation of the carrier (D) and signal baseband width (B).

$$SDR = 3.36 \times 10^{12} \frac{f_0^6}{N_T^2\ D^2\ B^2} \quad \ldots(6)$$

SDR, as is obvious from the above given expression, has a sixth-power dependence on the carrier frequency as in the case of SCR discussed earlier. Table 4 gives expected Signal-to-Distortion Ratios for the frequencies of our interest (800 MHz, 1 GHz, 2.5 GHz and 12 GHz) assuming a fairly perturbed ionosphere ($N_T = 10^{18}$ electrons/m^2), a 4.5 MHz TV baseband (525 line, 60 fields/second system), and a rms frequency deviation of 8 MHz (corresponding to an RF channel about 50 MHz in width).

TABLE 4

SIGNAL-TO-DISTORTION RATIO IN BASEBAND DUE TO IONOSPHERIC DISPERSION OF THE WIDEBAND FM SIGNAL (TV RELAY)

Frequency, GHz	Signal-to-Distortion Ratio, in dB
0.800 GHz	35.92 dB
1.000 GHz	36.42 dB
2.500 GHz	38.80 dB
7.000 GHz	41.49 dB
12.000 GHz	42.89 dB

Caution should be exercised in equating the subjective effect caused by SDR in the output of an ionospherically dispersed FM transmission with that of a similar Signal-to-Noise ratio in the output of a conventional vestigial-sideband AM transmission corrupted by thermal noise. The spectral density of thermal noise in the video baseband is uniform in AM-VSB transmission whereas that of the intermodulation in the FM transmission goes roughly as the square of the baseband frequency. Thus it affects the high-frequency video content more than it does the low-frequency portion of it. Also, thermal noise is generally uncorrelated with the signal whereas the intermodulation noise can display a strong correlation. Therefore, the intermodulation can be expected to differ in appearance and subjective effect from the customary "snow". However, since intermodulation noise is introduced by the ionospheric segment of the earth-space or space-earth channel, its magnitude could be considerably lowered by the use of pre-emphasis and de-emphasis techniques that by nature discriminate against channel-contributed noise.

Ionospheric propagation of wideband FM signals has some other implications for video signals. One of them is that the intermodulation may affect the sound subcarrier, which is located above the video at 4.5 MHz because the intermodulation spectrum is at its strongest in the highest part or topmost part of the modulating baseband. Adverse affects may be eliminated by using a relatively strong FM subcarrier and relatively smaller peak frequency deviation of the subcarrier or by establishing a separate audio link. The situation is less promising with respect to color TV which uses a subcarrier at 3.58 MHz with its attendant sidebands extending from roughly 2.5 to 4.5 MHz, again in the vicinity of the peak of the intermodulation spectral density[13], to carry hue and saturation information. One could anticipate two effects. First, the ratio of linear-signal-to-intermodulation spectral density at which color information

must be demodulated (corresponding to the Signal-to-Cross-Talk Ratio discussed earlier in this section) will be unfavorable, amounting for 29-30 dB (at 1 GHz carrier frequency). As a result, the color quality will be degraded. Secondly, the intermodulation can be expected to interfere with the synchronization of the color subcarrier generated in the receiver. The color subcarrier is suppressed at the transmitter and only short bursts (8 cycles of 3.58 MHz) are sent at the beginning of each horizontal line (that is, at 15.75 kHz rate). Because quadrature modulation is employed, the reference oscillator must be synchronized in phase as well as in frequency and any phase error would degrade color separation.

One should keep in mind that transionospheric propagation effects are at their strongest in the UHF broadcasting-satellite service allocation. As one moves up to higher frequency bands, intermodulation effects caused by dispersion regress by the sixth-power of the frequency as discussed earlier and are almost negligible beyond S-band frequencies. Effects on 2500-2690 MHz band are not expected to be critical but color TV broadcasting using wideband FM from space in the UHF (620-790 MHz) band may suffer from group delay distortions that exceed prescribed limits and result in a differential phase characteristic poorer than recommended. However, no definite words on this and other ionospheric dispersion effects will be available until forthcoming NASA-India UHF Satellite TV broadcasting experiments are completed in 1974-75.

3.1.2 Atmospheric Attenuation

The major attenuation producing agents in the atmosphere are neutral oxygen, water vapor and liquid water. Oxygen and water vapor absorb microwave energy; liquid water, in the form of clouds and rain, both absorbs and scatters it. These same agents increase the atmospheric noise temperature, an effect that is significant in communication systems utilizing relatively low-noise receiving techniques. The change in system noise temperature due to atmospheric attenuation can be expressed as:[6]

$$\Delta T_s \approx \left(1 - \frac{1}{L}\right) (290 - T_c), \quad °K \qquad ...(7)$$

where, L = total atmospheric attenuation in terms of power ratio ($L>1$)
T_c = contribution to the receiving system noise temperature from noise sources beyond the precipitation and clouds, as estimated without regard to atmospheric attenuation.

The total effect of attenuation and change in system noise temperature reduces the ratio of received carrier power to system temperature ratio (C/T) by a factor

$$L \frac{T_s + \Delta T_s}{T_s} = L + (L - 1) \frac{290 - T_c}{T_s} \qquad ...(8)$$

where T_s is the receiving system noise temperature (°K).

Other than moisture, the atmosphere is composed of a variety of gaseous elements, the most prominent of which are Nitrogen, Oxygen and Argon.[22] Although Nitrogen constitutes some 80 percent of the entire atmosphere, it plays no part at all in absorption of microwaves because the nitrogen molecule possesses no permanent dipole moment, either electric or magnetic.* The oxygen molecule possesses a small magnetic moment which enables it to display a group of absorption lines between 54 and 120 GHz. They consist of a group of lines lying between 54 and 66 GHz together with one isolated line at 119 GHz. Due to collisions between oxygen molecules, the lines clustered around 60 GHz are quite broad, their "wings" extending to low enough frequencies to cause significant absorption in the frequency range from 2 to 14 GHz. In addition to the resonant absorption, oxygen also displays a non-resonant absorption extending continuously throughout the spectrum. In the frequency range 2-14 GHz, this absorption is practically independent of frequency. Although it accounts for more than 80 percent of the total absorption due to oxygen in this range, the small increase in absorption that may be observed with increasing frequency is due almost entirely to the resonant component of the absorption. Molecular oxygen absorption in the frequency bands of our interest (<14 GHz) is rather small.

Moisture absorption of microwave energy is altogether a different story and is very much dependent on the frequency. In both gaseous and droplet form, moisture possesses significant absorption capability in the frequency bands of our interest. However, the mechanisms and characteristics of absorption by water vapor and water droplets are very dissimilar and need to be treated separately.

Water vapor is a molecular gas and absorbs microwaves in the same manner as does oxygen, that is, through transitions between different molecular energy states. Because, unlike oxygen, water vapor molecules possess a permanent electric dipole moment, it is more responsive to excitation by an electromagnetic field than is oxygen. State transitions, responsible for absorption of microwave energy, have resonant frequencies at and above 22 GHz. Thus, water vapor absorption is significant even at quite low concentrations. For an earth-space communication link, the actual absorption or the corresponding increase in Sky Noise is a function of the range, frequency and elevation angle. In the worst case (some 5° elevation and an unusually heavy water vapor concentration of 20 gms/m^3), combined water vapor and oxygen contribution to the sky noise at 1 GHz is approximately 20°K. At the resonant frequency (22 GHz), the combined absorption peaks to some 200°K. Beyond 7-8 GHz, the water vapor absorption increase is rather steep. Detailed numbers for various situations can be found in a paper by Feldman.[18] Figure 3, taken from Feldman's paper[18], shows the Sky Noise contribution from various sources at 10° elevation and clearly illustrates the combined effects of water vapor and oxygen absorption.

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*Argon exhibits negligible absorption in the frequency bands of our interest. Trace gases, with atmospheric abundance less than 0.1 percent, cannot produce appreciable absorption since the absorption capability of any gas is proportional to its density.

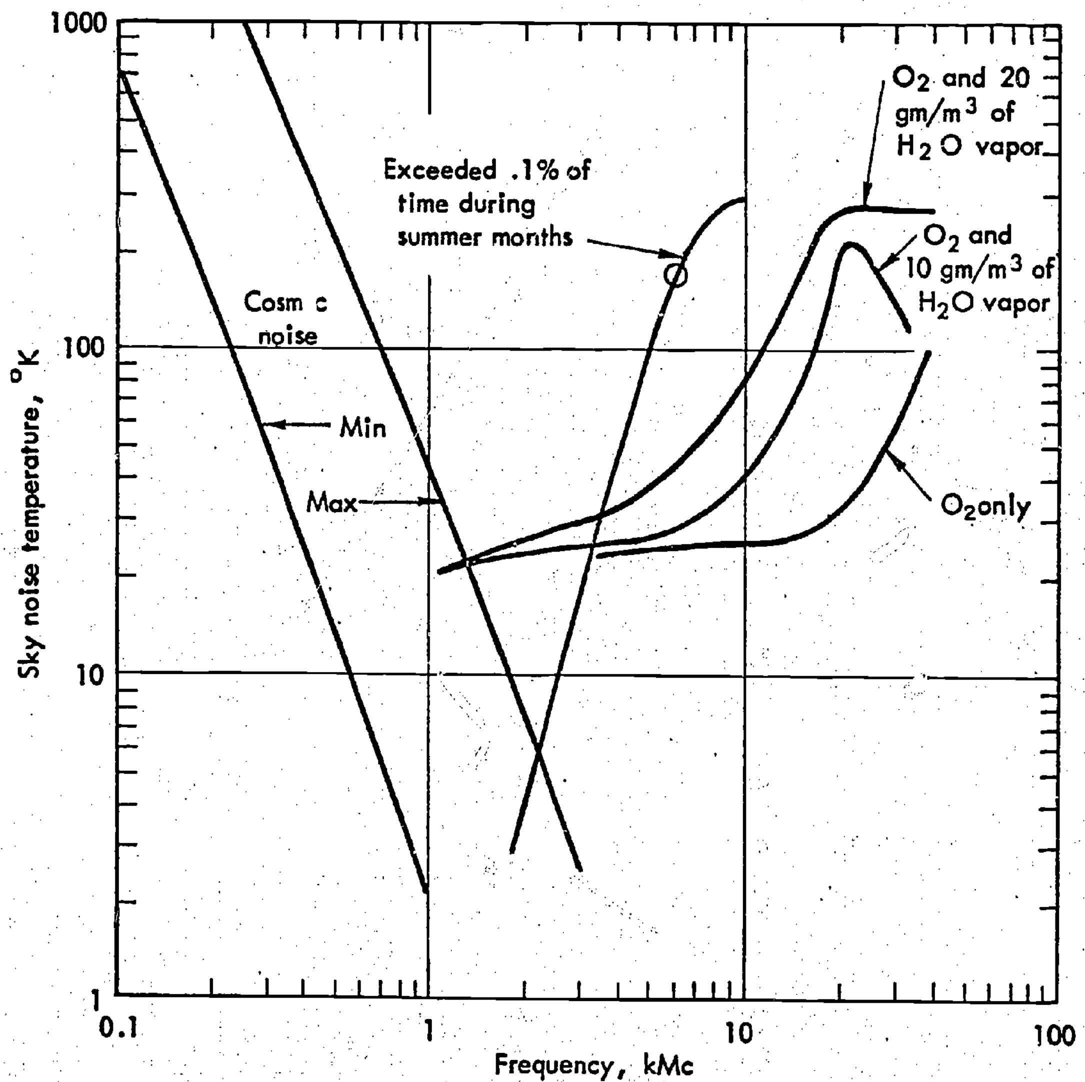

Figure 3. Sky Noise Temperature at 5^0 Elevation[18]

Clouds and fog are comprised of very small water droplets and here the absorption is the dominant mode of attenuation. Attenuation due to clouds and fog is very much independent of droplet size as long as the total mass of water droplets in a given volume of the atmosphere is fixed. Holzer[19] has given a plot of the coefficient of attenuation in clouds as a function of frequency at 0°C. The coefficient, expressed in dB/km/gm/m^3, has a value of 0.04 at 5 GHz which increases to 0.15 at 13 GHz and 1.0 at 33 GHz. Temperature also affects cloud introduced microwave attenuation. The attenuation increases as the temperature of the water in clouds decreases until the transition from water to ice is passed, at which point a new dielectric constant takes effect and the attenuation becomes considerably less.

The attenuation in clouds is given by

$$A_c = k\rho r \quad \text{dB} \qquad \ldots(9)$$

where k is the coefficient of attenuation (dB/km/gm/m^3) discussed in the earlier paragraph, ρ is the liquid water content of clouds in gm/m^3, and r is the path-length through the cloud in km.

Precipitation in the form of rainfall is the largest factor in atmospheric attenuation in the temperate regions of the world. As in the case of clouds, the size of the water droplets and distribution of these sizes along the propagation path are the controlling factors. Even in light drizzles, the droplets are large enough so that contribution due to scattering is no longer negligible and the actual attenuation dependence on frequencies is a mixture of second-power and fourth-power dependence relationships.*

Some degree of correlation has been found between the droplet size distribution and the rate of rainfall. The latter quantity is reliably recorded at most places and offers a reasonable basis for attenuation estimates. The signal attenuation in rain is given by

$$A_p = qpr \quad \text{dB} \qquad \ldots(10)$$

where, q is the coefficient of attenuation in dB/km/mm/hr (mm/hr representing the rate of rain fall, p is the rainfall rate in mm/hr, and r is the path-length through the rain in km).

q, the rainfall attenuation constant, is a function of the frequency of the incident radiation, rainfall rate (mm/hr) and temperature. For moderate rainfall rates (10 mm/hr), the coefficient of attenuation is 0.0003 for frequency with a 10 cm wavelength and increases to 0.02 dB/km/

*Even at 15.3 GHz, satellite-to-earth experimental link data[16] show excellent agreement with the attenuation model based upon the assumption that attenuation is predominantly due to absorption rather than scattering. However, one should be aware of the interference implications of precipitation scattering on the terrestrial service receivers operating in the same band. For details, see Buige et al.[26]

mm/hr for a frequency with a 1 cm wavelength.

For the sake of completeness and better understanding, Holzer's model atmosphere for temperate regions has been reproduced in Figure 4. The horizontal extent of rainfall (E) is given by the empirical relationship:[23]

$$E = 41.4 - 23.5 \log_{10} p \quad \text{km} \qquad \ldots(11)$$

where p is the rainfall rate in mm/hr as mentioned earlier. The vertical extent depends on the altitude where precipitation originates (about 3 km in temperate zones). Based on the atmospheric model shown in Figure 4, one can calculate attenuations due to clouds (A_c) and rains (A_p) and thus give the total attenuation (A_t) due to clouds, rain and atmospheric gasses.

$$A_t = A_c + A_p + A_g \quad \text{dB} \qquad \ldots(12)$$

where A_g is the attenuation due to gaseous absorption (in dB).

Figure 5 shows typical rain attenuation probabilities for various frequencies based on CCIR USSG Paper IV/1024, June 26, 1970. 2.5 GHz data is extrapolated from the attenuation coefficients given by Holzer.[19] Based on the data given in Figure 5, video $[S/N]_{p,w}$ probabilities for various frequencies are shown in Figure 6 for a 5 dB link margin (dB above 12 dB FM threshold), B_{rf}/B_v = 5.95, Satellite ERP of 57.5 dBW, and B_{rf} = 25 MHz.* Calculations assume use of pre-emphasis and de-emphasis operations on the video signal prior and after demodulation, respectively, and 50 percent reduction in the peak-to-peak frequency deviation of the carrier due to pre-emphasis (see Ref. 28). The advantages of using S-band allocation are clearly visible.

Interest in future domestic satellite systems coupled with the fact that the standard 4 and 6 GHz bands are going to be congested in the near future has led to the experimental investigation of atmospheric propagation effects on frequencies above 10 GHz. Prominent among these experimental programs are millimeter wave propagation experiments associated with NASA's ATS-V satellite (15.3 GHz and 31.65 GHz)[24], the sun tracker setup at Bell Telephone Laboratories[27], and precipitation scatter experiments at COMSAT[26]. Figure 7 shows cumulative distribution of 15.3 GHz carrier attenuation for a one year period at NASA's Rosman (North Carolina) ground terminal based on directly measured satellite and radiometric data. It is clear that the link suffers from occasional deep fades (16-20 dB). These fades have serious implications for system designers because satellite

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*$[S/N]_{p,w}$ = Peak-to-Peak Signal to weighted rms noise ratio,

B_{rf} = Bandwidth of the modulated RF carrier,

B_v = Video Signal baseband width, and

ERP = Effective Radiated Power.

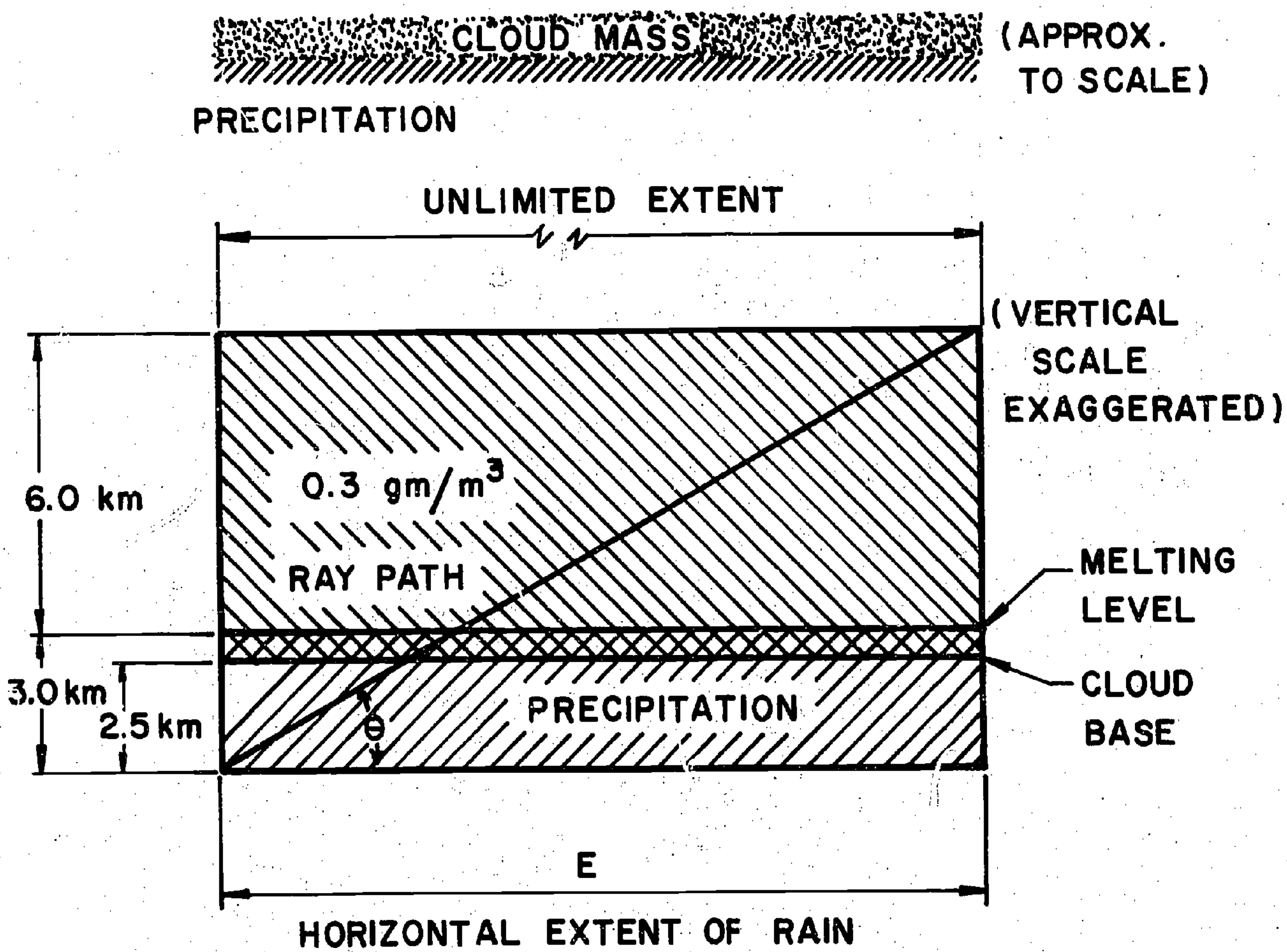


FIGURE 4. MODEL ATMOSPHERE FOR TEMPERATE REGIONS [19]

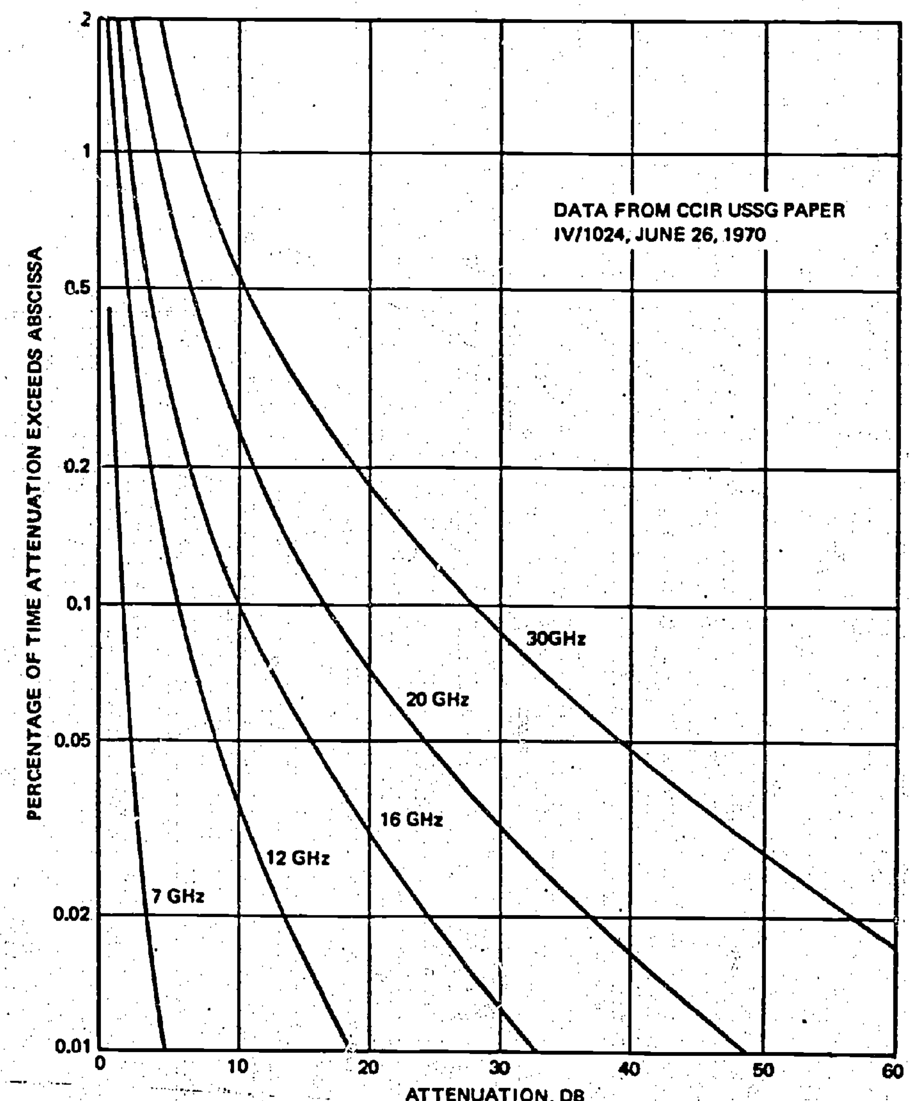


Figure 5. Rain Attenuation Probabilities in New Jersey

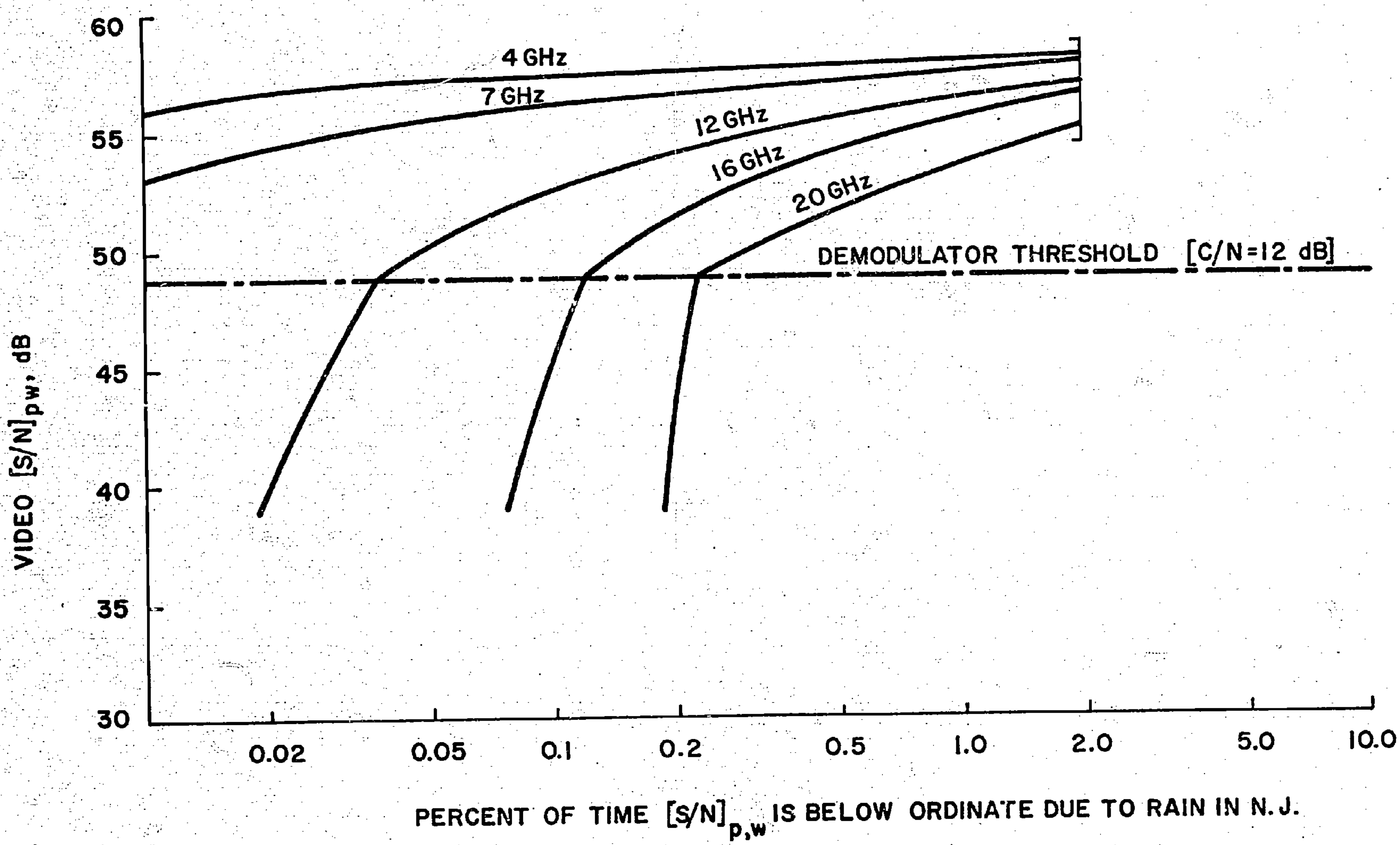
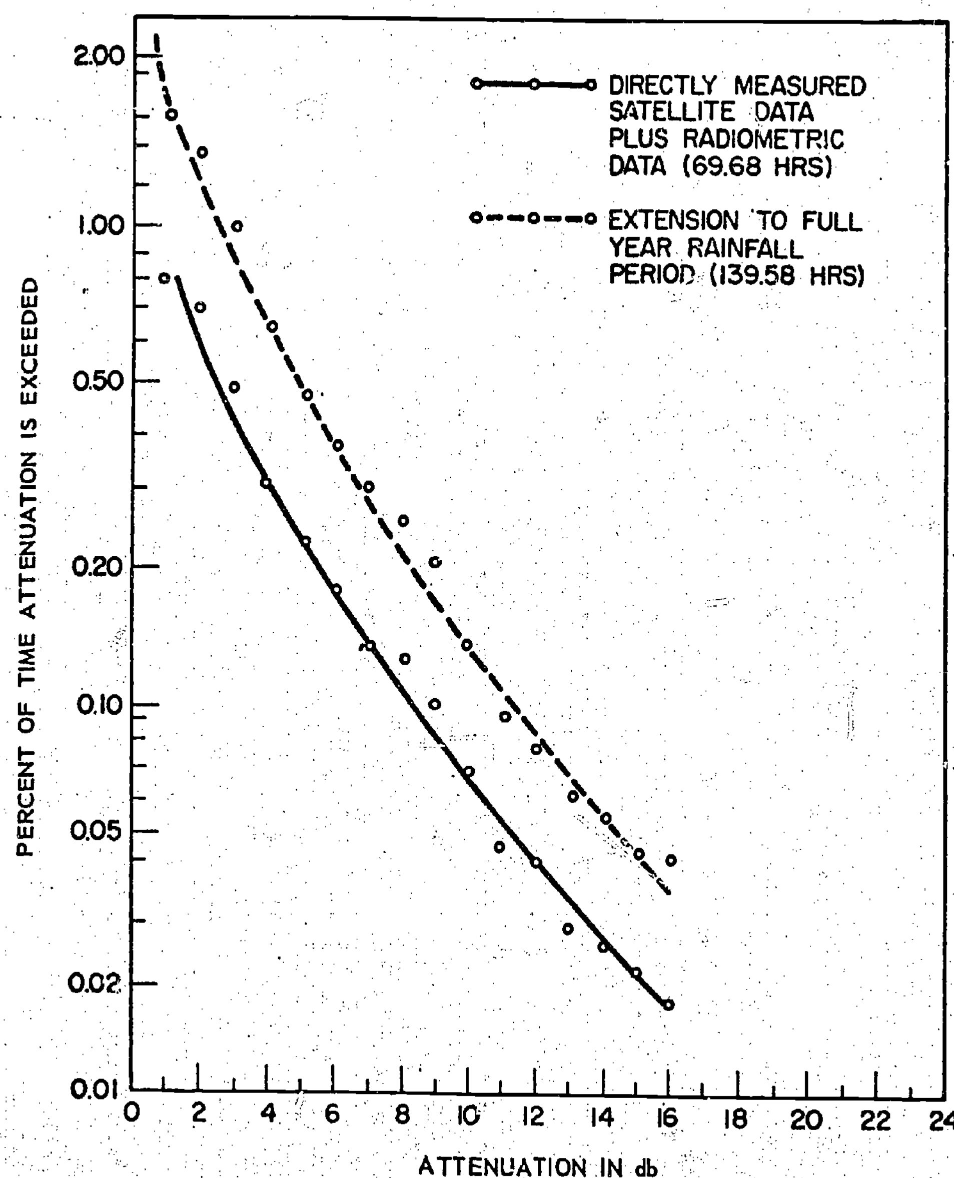


FIGURE 6 COMPARISON OF VIDEO $[S/N]_{p,w}$ PROBABILITIES FOR 4GHz, 7GHz, 12GHz, 16GHz, AND 20GHz DOWNLINKS FOR A LINK MARGIN OF 9.5dB ABOVE THRESHOLD AND A B_{RF}/B_V EQUALS 3.95 (B_{RF} = 25 MHz).



Cumulative Distribution of 15.3 GHz Carrier Attenuation for 1 Year Period (10/1/69 to 9/30/70) At Rosman, North Carolina, Based on Directly Measured Satellite Data And Radiometric Data.

Figure 7.

systems at best can afford only several dB of margin for attenuation by rain. Breaks in service are inevitable and a tradeoff must be made between the link reliability and the link margin. The amount of service breaks (time for which performance is below prescribed limits) that can be tolerated will very much depend on the application. For a service where a satellite is used to feed TV programs to various community headends, perhaps one could tolerate a link reliability of the order of 99.0-99.8 percent of time whereas in situations where a satellite is being used for machine-to-machine communication and data transmission, the reliability requirements may be of the order of 99.99 percent. As one can see from Figure 7, the link margin requirement for a 99.99 percent reliability is of the order of 22 dB (by extrapolation)whereas that for 99.9 percent reliability is 8.5 dB. Such link margin requirements are very taxing in terms of satellite power.

Fortunately, it has been established that most intense rain that cause deep fades occurs in very limited cells and that the rain which covers large areas (square miles) falls at the rate of 25 mm/hr or less. This leads to the use of duplicate ground stations far enough removed so that there is little likelihood that an intense rainstorm will cover both ground stations at the same time, i.e. so-called "space diversity". If the attenuation statistics on the two paths are uncorrelated and enough margin is provided to make both outages small, the system outage time can be reduced to a satisfactory degree by switching to the other ground-station when the one is experiencing severe fades due to localized heavy rain cells. In the 15.3 GHz ATS-V diversity measurements conducted at Ohio State University, fades were reduced by approximately two orders of magnitude by the use of a simple diversity system that was comprised of two ground-stations separated by 4 km.[16]

Although space diversity provides an important alternative for combating short-term and localized deep fades due to heavy rains at frequencies above 10 GHz, it has certain limitations particularly from the viewpoint of small-terminal roof-top type operation. Siting duplicate earth-stations some 4-10 km apart is a reasonable solution for a system that has a small number of rather complex earth-stations handling heavy traffic. But it certainly does not make sense in a situation where the ground segment consists of a large number of small and relatively low- or moderately-priced earth-stations and particularly when one is attempting to locate earth-terminals in the near vicinity of the redistribution facility/ground headend in order to bypass the local telephone plant, common carriers and the need for any terrestrial interconnection facilities between the earth-station(s) and the redistribution facility. In such a situation, one has only two options: (1) To accept a lesser link reliability, or (2) To use a commandable spot-beam concept proposed by Kiesling and Meyerhoff.[15]

Kiesling and Meyerhoff[15] have outlined a novel scheme for combating localized deep fades that is based upon a high-power spot beam capability in the satellite which is commanded over the normal command channel by the earth-station(s) experiencing fades greater than the standard margin. Satellite beam positioning is to be achieved by multiple feeds. Parametric studies by Kiesling and Meyerhoff[15] indicate solar cell and transmitter capabilities onboard the satellite for the commandable spot-beam technique

were much below that needed where a fixed-gain area-coverage antenna and associated transmitter were to accommodate these localized short-duration attenuation fades. Instead of solar-cells supplying the spot-beam directly for the short intervals required, batteries with low-duty cycles could be used (possibly shared with other spacecraft sub-systems) to reduce the satellite payload.

Penalties associated with the spot-beam scheme include additional earth station capability and cost to handle at least two different frequencies, and additional satellite antennae with multiple feeds, transmitters, switches and batteries. On the positive side is the reliability measure attainable for reasonable-sized satellite transmitters and power supplies greater than 10 GHz. The cost involved in providing additional capabilities at the earth-station is considerably less than that involved in duplicating a similar earth-station 4-10 km apart and interconnecting them via microwave. However one should also recognize some of the limitations of the spot beam technique. It is suited to an environment of receive-only stations such as the ones employed for TV program distribution. However, it creates certain beam switching problems when it is employed in an environment of receive-transmit earth-stations, particularly those handling voice and data traffic on a point-to-point basis. Also, it alleviates the short-duration fading problem only for the downlink. The uplink still has to be oversized to compensate for the heavy rain-induced attenuation. In the case of standard Frequency Division Multiplexed-Frequency Modulation/ Frequency Division Multiple Access (FDM-FM/FDMA) operation, this would necessitate a close monitoring of atmospheric conditions and automatic control of the earth-station transmitter output over a wide range (15-16 dB) to maintain earth-station induced signal strength at the satellite transponder input within 0.5 dB of the prescribed value and to ensure proper power sharing among the various carriers.

After a careful consideration of these factors and the ones described in the forthcoming sections, we are of the opinion that all educational satellite services/systems involving interaction capability should be accommodated in the 2500-2690 MHz frequency band. As discussed earlier in this section, S-band frequencies are relatively immune from heavy-rain induced attenuation. For 99.99 percent link reliability, the link margin for the 2.5 GHz band is of the order of 2.5-3.0 dB (Figure 5) whereas the link margin for the 12 GHz band is of the order of 18-19 dB. The only problem with the 2.5 GHz band is that it is allocated by the WARC for Broadcasting-Satellite Service (BSS) in all the ITU regions (see Section 2.2.2 and Appendix A). For Fixed-Satellite Services, relatively narrow bands are allocated on the extremes of the 2500-2690 MHz band--2500-2535 MHz for "downlink" and 2655-2690 MHz for "uplink" transmissions. The current U.S. position is to use these rather narrow assignments for the purposes of demand assignment multiple access communication in remote and isolated areas. To make use of the 2500-2690 MHz in the United States for the delivery of various educational services that may also involve limited interaction, that is, some sort of a return link from the user to the central source via satellite, internal rulemaking would be necessary to incorporate necessary modifications in the original WARC allocation.

As far as the uplink transmissions are concerned, the 2655-2690 MHz Fixed-Satellite allocation could be used. However, it has rather limited capability in terms of the number of accesses it could accommodate. Education interests should explore the possibility of additional frequency space in the neighborhood of S-band to enlarge uplink transmission capabilities. As discussed in Sections 6 and 7, it seems doubtful that in the future, a 6 GHz uplink would be permitted from antennae with sizes less than 25-30 feet diameter. The only alternative for small terminal uplink transmissions, in case the demand exceeds the capabilities of the 2655-2690 MHz band, would be to use 13 GHz. This choice would be excessively costly and inconvenient from the viewpoint of transmitter power amplifier and uplink power coordination requirements. Where a large number of independent low-data rate return links are needed, 13 GHz has its own problems (see Section 6). In a typical broadcasting or TV program distribution situation where there are relatively few uplinks to be maintained, use of 13 GHz is not all that much of a problem.

One of the alternatives that we would like to see explored is the division of the 2500-2690 MHz band for asymmetrical uplink and downlink allocations--2500-2570 MHz for earth-to-space link and 2570-2690 MHz for space-to-earth link with earth-to-space transmission allocation in this band limited to the accommodation of low-data rate return links from small earth-stations. Transmission directions are the reverse of Fixed-Satellite allocations in the same band to permit frequency reuse with suitable separation between educational satellites and commercial satellites.

3.2 Natural-Environmental Noise

In the previous section, we concerned ourselves with the ionospheric and atmospheric propagation effects on UHF and microwave frequencies and the atmosphere's contribution to the system noise that arises due to absorption of the radiated signal energy. In this section, we shall discuss the contribution of the following sources of external noise that contribute to the overall system noise: (1) Terrestrial; (2) Solar; and (3) Galactic. Indigenous or man-made noise shall be the subject of the next section.

Any hot body radiates energy at all frequencies. The distribution of energy as a function of frequency radiated by an ideal black body is given by Planck's radiation law or the Rayleigh-Jeans approximation to this law which holds fairly well at the microwave frequencies.[29] Discrete thermal sources are replaced by equivalent black bodies everywhere in the field of view of the antenna to derive the formula for antenna temperature (T_A). The system noise temperature (T_S) is the sum of the Antenna temperature (T_A) and Receiving System noise temperature (T_R).

A single discrete source occupies a small cone of solid angle in the antenna pattern. It radiates thermal energy according to the Rayleigh law through this cone to all parts of the antenna. An

integration is performed over the whole antenna to find the total power available at its terminals from single discrete source. A second integration is performed over the entire antenna pattern to add the contributions from all the discrete sources to the power at the antenna terminals. Thus, the antenna noise temperature is given by[29,30]:

$$T_A = \frac{1}{4\pi} \iint G(\Theta,\phi)\ T(\Theta,\phi)\ \sin\Theta\ d\Theta\ d\phi \qquad ...(13)$$

where, $G(\Theta,\phi)$ = Normalized Gain function of the Antenna
$T(\Theta,\phi)$ = Distribution of the temperature over all angles about the Antenna
Θ,ϕ = Spherical polar coordinates about the antenna.

The frequency spectrum of the cosmic noise component extends from about 20 to 4,000 MHz. Although generally isotropic in nature, the cosmic noise intensity is greatest from the direction of the galactic center (the gravitational center about which our sun revolves) and least from the direction of the galactic poles. The maximum and minimum values of intensity are shown in Figure 3 and represent the cosmic contribution to the ENT (Equivalent Noise Temperature) environment of an earth-space communication system whose antenna beam subtends no more than the apparent radiating area of the particular galactic region.

The other contributors to the antenna noise temperature are discrete noise sources such as sun, moon, radio stars, earth, etc. Their contribution to the antenna noise temperature is determined by the expression given above. Of the discrete sources, the sun is the largest potential contributor to the antenna temperature. (Because of its small angle of subtension, it is a factor only when in the main lobe of the antenna.) With the sun's disc completely within the antenna beam, the sun contributes a temperature, T, given by

$$T = \frac{(290 \times 675)}{f \times 10^{-9}} \quad \text{degrees K} \qquad ...(14)$$

where f is the frequency in Hz. One should also recognize the fact that the sun's contribution is also dependent upon its state--whether it is quiet or disturbed. A disturbed sun has a higher contribution to the ENT. For a general case, the effective antenna temperature contribution from the sun (T_{SA}) is given by[30]:

$$T_{SA} = T_{SB}\ [\Omega_S/\Omega_B] \qquad ...(15)$$

where T_{SB} is the brightness temperature of the sun (in °K), Ω_S is the solid angle subtended by the sun in steradians ($\approx 6.3 \times 10^{-5}$ steradians), and Ω_B is the solid angle of the antenna main beam in steradians, Ω_B in steradians is related to the antenna beamwidth by the relation

$$\Omega_B = [\theta_B \ \phi_B/3280] \qquad \ldots(16)$$

where θ_B and ϕ_B are the antenna beamwidths in the θ and ϕ direction respectively and are expressed in degrees. For the case of a parabolic antenna, a symmetrical pattern antenna, $\theta_B = \phi_B$.

Complete evaluation of solar noise contribution to ENT also demands data on noise power radiated, that is, the periods when the sun is disturbed and when it is not, and also the periods when the sun will be in position to effectively increase antenna noise temperature. As far as the former is concerned, exact statistics for sun disturbances are not available. However, it is known that the disturbances are more frequent and intense near sun spot maxima. However, as far as the latter is concerned, that is, the times when antenna beam will be looking directly into the sun, one can calculate and predict the system outages due to the sun (see Ref. 30, Appendix B, Figures B-1 & B-2) and the range of noise contribution for a given receiving antenna location, receiving antenna beamwidth, and frequency of operation.

As far as terrestrial noise contribution to ENT is concerned, it originates from the semi-black-body radiator nature of the earth. A true black body has an absorptivity (A) of unity for incoming radiation, and a reflectivity (R) of zero. For an opaque, gray body, the sum of absorptivity and reflectivity is always unity ($A + R = 1$). By Kirchoff's law, the emissivity, or ratio of the thermal electromagnetic power emitted by a gray body to that of a black body at the same temperature, equals the absorptivity (A), and hence equals ($1 - R$). Therefore, the earth's effective noise-radiation temperature (T_E) is

$$T_E = T_t(E)\ (1 - R) \qquad \ldots(17)$$

where $T_t(E)$ is the thermal temperature of the earth, and R is the reflectivity of the terrain viewed by the antenna. IEEE standard reference temperature for receiver noise-factor measurement (T_0) is 290°K and can be used as a convenient value for $T_t(E)$. Reflectivity of the ground varies from nearly unity for smooth water viewed at glancing angles, to nearly zero for rough, dry ground viewed at steep angles. Ground noise contribution to antenna temperature for ordinary minor-lobe levels varies from about 20 to 60°K, but may be reduced to a very few degrees by careful design for minimum back and side lobes.

In addition to sun and earth, there are numerous other discrete noise contributing sources (known as radio stars), each generally less than 1° in extent. The strongest of these discrete noise sources show a tendency to occur near the plane of the galaxy. In general the noise contribution from a single radio star is minor relative to the galactic background unless extremely high-gain, narrow-beam antennae are pointed in the direction of the star. The stars Cygnus A and Cassiopeia A are among the more potent noise sources.[29] Galactic noise is known to vary with frequency approximately as $f^{-2.5}$ and is essentially negligible above 1 GHz.

In Sections 3.1-3.2 we discussed the frequency dependence and prominence of various external noise sources along with propagation effects. At this point we would like to indicate that although noise from external noise sources cannot be altogether eliminated, it could certainly be minimized by designing the antenna for low side and back lobes. The minimum attainable noise temperature of an ideal antenna in various parts of the microwave frequency spectrum can be calculated by assuming that the only noise is that entering via the main-beam and that the sun is not in the main-beam. Blake[31] has calculated such minimum and irreducible noise temperature for an ideal ground based antenna for a wide range of frequencies (100 MHz-100 GHz). Figure 8 presents Black's plot.

Below 1 GHz, the upper limit of the noise temperature band applies to the main beam directed towards the galactic center. Above 10 GHz, the upper limit applies for a main beam at low elevation angles, but still not looking towards any part of the earth itself. The bottom edge of the band applies for the same respective portions of the figure for main beams directed towards the galactic poles or towards the zenith. These extreme values are attained only with rather narrow-beam antennae--say, less than 10 degrees, or ideally about one degree beamwidth or less. Wider beams will result in values tending towards the center of the noise band, regardless of the beam direction. As it is labeled on the Figure 8, below 1 GHz, it is galactic noise that is the dominant contributor to the antenna noise whereas in the 1-10 GHz band (often known as the "radio window") all noise contributions are rather small. Above 10 GHz, atmospheric noise (oxygen and water vapor absorption) raises the antenna noise temperature, and the effective temperature seen by an antenna can approach 200-250°K. For these reasons, use of cooled and extremely low-noise receiving systems is only meaningful in the 1-10 GHz frequency band. Beyond 10 GHz, where antenna noise contribution can be more by an order of magnitude than the receiver noise temperature, nothing is to be gained by application of cryogenically cooled receiving systems.

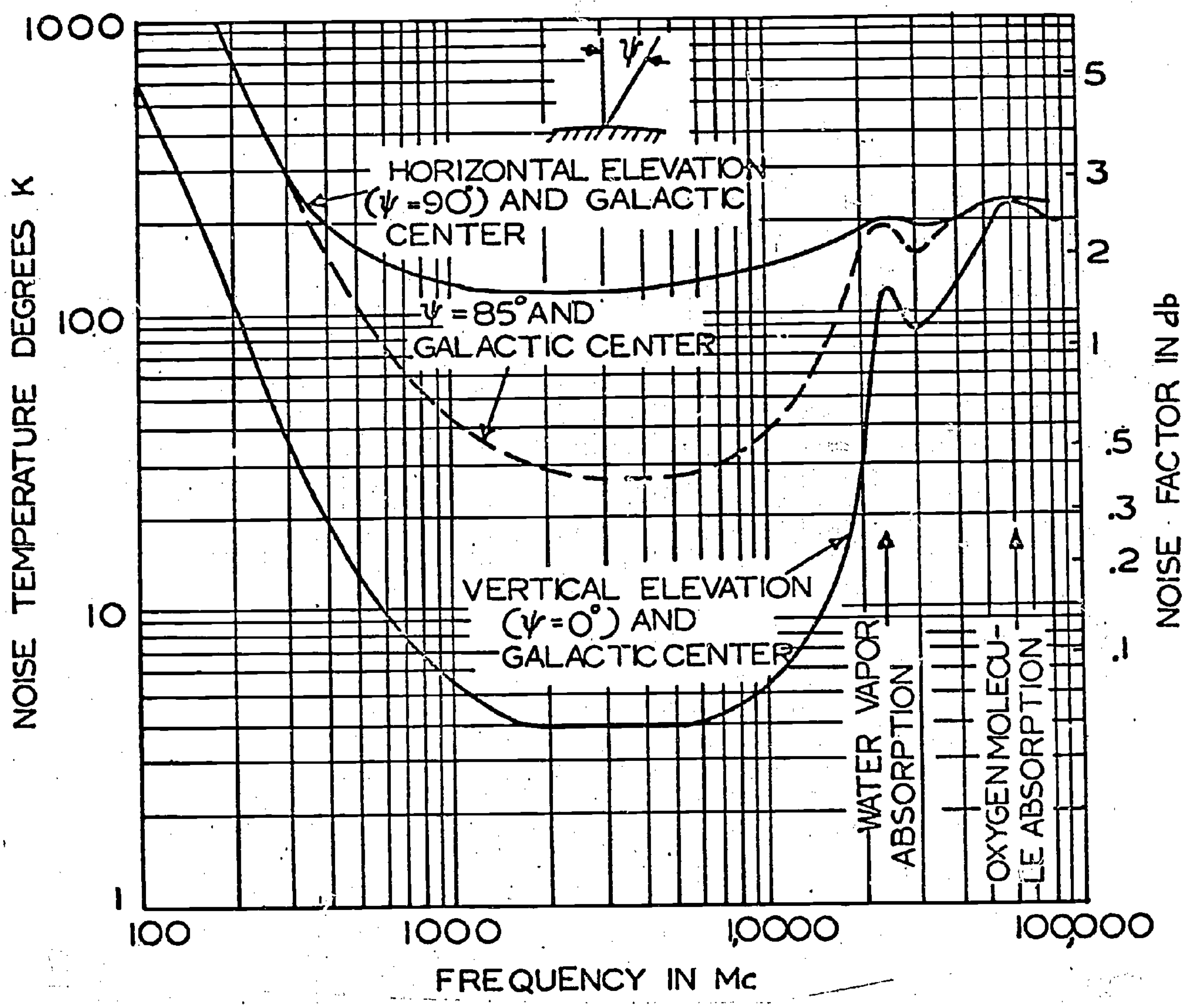


Figure 8. Irreducible Antenna Noise Temperature As A Function of Frequency and Elevation [Ref. 31]

4. MAN-MADE ENVIRONMENTAL EFFECTS

The effects of man-made environment on Broadcasting-Satellite or Fixed-Satellite services can be classified into two categories: (1) Those which put certain limitations on the communication links in terms of radiated power, power-flux density (PFD), and/or modulation technique; and (2) Those that contribute to the system noise in a manner similar to that of natural external sources discussed in the previous section.

The man-made factors that contribute to the various limitations on the communication link in terms of radiated power, direction of transmission in a particular frequency band, power-flux density on earth's surface, earth-terminal location and modulation are direct results of the planned frequency sharing between terrestrial and space services in frequency bands of near-term interest. In most frequency bands of current interest, particularly all below 10 GHz, terrestrial services were the first to be introduced. Space communication allocations were made only in 1963 (see Section 2.2.1) and the near-term technical and economic feasibility of space systems dictated use of the frequency bands on a shared basis. To avoid chaos, certain coordination between the various services in the same bands becomes a necessity. Figure 9 shows the possible interference paths between terrestrial and communication-satellite systems operating in the same frequency band. Various limitations on the communication links in both services are used to limit the interference from one service to the other to an acceptable level. One should recognize the fact that interfering signals at the input of a particular receiving system contribute to its overall system noise.

These man-made and deliberately imposed restrictions on the communication links of both Fixed-Satellite and Broadcasting-Satellite Services have certain important and distinct technical and economic implications for systems operating in each frequency band. The implications are distinct for each frequency band because the limitations for various frequency bands differ according to the power-flux-density limitations (see Figure 2), coordination procedures, and the extent of congestion in that band in terms of active systems. For example, the frequency band 620-790 MHz is heavily utilized in the USA for terrestrial UHF-TV broadcasting purposes and any broadcasting-satellite service, within the PFD limit imposed by WARC, would receive severe interference from relatively omnidirectional and high-power (in kilowatts) emissions from TV transmitters. In the 2.5 GHz band, shared with the relatively low-power Instructional Television Fixed Service (ITFS), minimum separation of receiving site ITFS transmitters with omnidirectional antennae would be of the order of 25-45 miles. With certain protection measures such as the use of directional antennae for the ITFS transmitters, cross polarization, site shielding, etc., it would be possible to reduce the minimum separation requirement to some 0.05 miles.[48 However, there is a price to be paid in terms of money to provide necessary protection measures. Without adequate protection measures it would not be possible to provide an economical satellite service to certain metropolitan areas where ITFS installations are clustered (see Ref. 53, Figure 8).

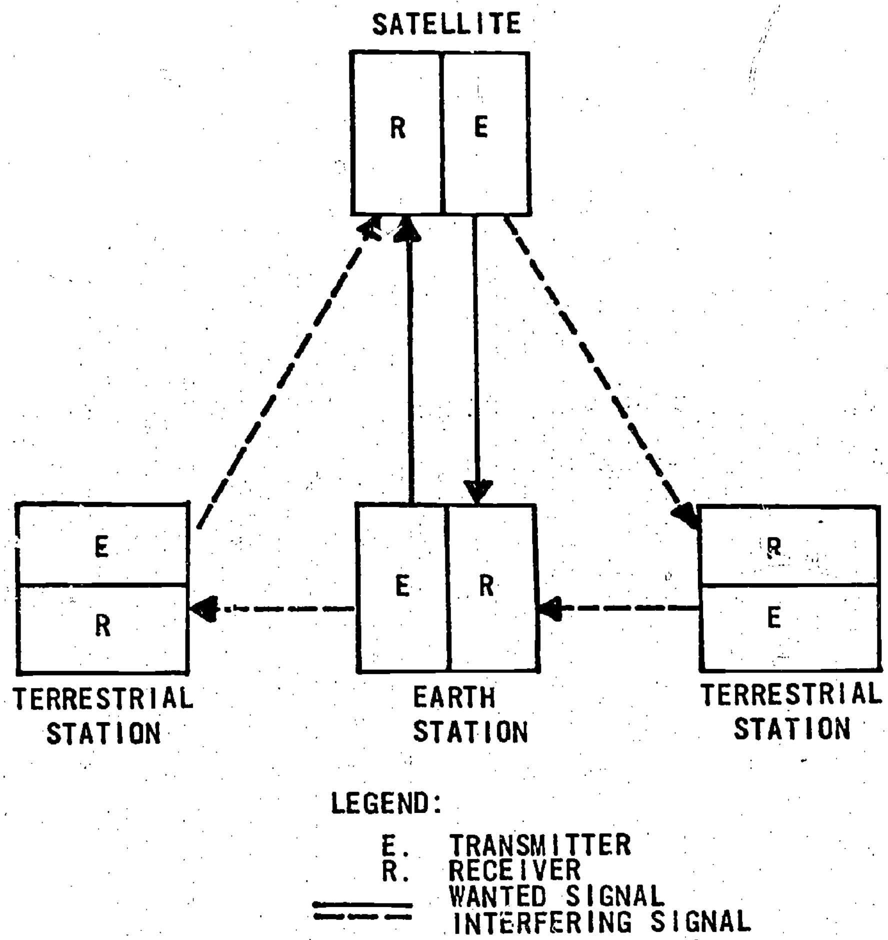


Figure 9. Interference Paths Between Satellite Systems and Terrestrial Systems Operating in The Same Frequency Bands [Ref. 46]

For 4/6 GHz operation, the operational environment is such that it is generally impossible to colocate an earth-terminal in the proximity of a distribution/redistribution/networking headend in any major urban location. It is said that it takes some $150,000 worth of effort merely to clear the site for a receive-transmit type earth-terminal of the 4/6 GHz frequency bands.[1] The 7 GHz band (6525-7125 MHz), currently used by the TV broadcasters for studio-to-transmitter interconnection purposes, is expected to have a more severe colocation problem than the 2.5 GHz band because the terrestrial systems in the former band use Frequency Modulation which increases the protection ratio requirement. Without any protection measures, the minimum separation needed between a terrestrial transmitter and an earth-terminal capable of receiving in the 7 GHz television distribution-only band is of the order of 80-90 miles. Again, with the protection measures described in the case of 2.5 GHz, the minimum separation requirement could be reduced to 0.5-1.0 miles. In the 12 GHz band, the terrestrial usage in the United States is virtually nil and no further sharing is planned. Thus, there is no colocation problem for 12 GHz operation.

In addition to the colocation problem, sharing considerations have also limited the maximum power-flux density on the earth's surface that could be emitted in a particular service by the satellite. These limitations (Figure 2) restrict the capabilities of the various downlink frequency options in terms of small-earth terminal operation. 2.5 GHz and 12 GHz are the only frequency bands below 13 GHz which will permit an economical small earth-terminal operational environment (antennae sizes less than 10 feet diameter).

It is man-made or indigenous noise that contributes to the overall system noise and results in higher satellite power requirements. The main sources of indigenous noise are automobile ignition, electric power lines, rotating machinery, and switching transients. It is typically impulsive in nature with a high peak-to-RMS ratio and random in occurence. Urban indigenous noise decreases exponentially with frequency and is significant only for the UHF BSS and 2500 MHz allocations. Until recently, available data in this area have been few and often not comparable because of differences in measurement methods and conditions. A limited survey of rf noise in the greater Cleveland (Ohio) areas was undertaken under NASA auspices during 1967 at 480 and 950 MHz and during 1968 at 0.3, 1 and 3 GHz in Phoenix (Arizona). So far only scattered results are available.[36] However, the available results have made it clear that the major source of man-made interference is automobile ignition, and that average radio frequency noise levels (dB above kTB) for Cleveland at 950 MHz was 11 dB for noisy sites and 6 for quiet ones.

As in the case of natural external noise contribution to the antenna, the man-made noise component of the antenna noise temperature is given by

$$T_A = \frac{1}{4\pi} \int_{4\pi} T_1 \, G \, d\Omega \qquad \ldots(18)$$

integrated over 4π steradians. T_1 represents the effective brightness temperature of man-made noise, G is the antenna power gain relative to an isotropic antenna, while Ω is the solid angle. If Ψ is the highest angle of arrival for man-made noise, and $\bar{G}_1$ the average gain over all directions with elevations between 0 and Ψ, then T_A can be expressed as the following, provided the brightness temperature is reasonably constant over these directions,

$$T_A \approx [\bar{G}_1 \ \Psi/2] \ T_1 \qquad \ldots(19)$$

Clearly, any experimental data stated in terms of antenna noise temperature must be viewed with the characteristics of test antenna in mind.[6]

The TRW Study on TV broadcast satellites[6] has assumed a 2000°K man-made noise contribution to antenna noise temperature for a 6-foot parabola at 900 MHz. Assuming xponential variation of the man-made noise and moderate antenna elevation so as to keep the sources of man-made noise outside the main-lobe (some 30° elevation), the man-made noise contribution to a system operating at 700 MHz is expected to be in the neighborhood of 3640°K whereas the same for 2.5 GHz is expected to be something like 200°K. At 12 GHz, under similar conditions, the man-made noise component of the antenna noise temperature would be around 6°K.

5. HARDWARE CONSIDERATIONS

Hardware state-of-the-art affects the selection of operational frequencies. Cost and performance of certain components of the total electronic system, be it satellite or the ground segment, show dependence on frequency. Such components can be identified as low-noise RF pre-amplification sub-systems, RF passive networks such as channel separation networks, RF transmission devices (waveguides and cables), RF-to-IF converters, and RF power output devices. In addition there are system components such as antennae whose size and weight are a direct function of the operational frequency. Hardware frequency dependence has been explored in the past by Feldman[37-39], Kane and Jeruchim[40], Bergin[41], Davis[42], Siegal[43], Hesselbacher[44], and in a Jansky and Bailey study[30] for NASA. In this section we shall draw upon these papers and reports to present a brief discussion on hardware frequency dependence for the sake of completeness.

The first sub-system that is affected by the choice of the operational frequency and in turn affects its choice is the receive/transmit antenna--be it a part of the satellite or the ground-station. From basic antenna theory, we know that gain of an antenna (over an isotropic radiator) is given by $[4\eta\pi A_T/\lambda^2]$ where A_T is antenna's effective area, η is the efficiency of the antenna and λ is the wavelength of incident/transmitted radiation. Thus, the gain of the antenna shows a second-power dependence on frequency because the product of the frequency and wavelength of electromagnetic radiation is always the velocity of light $[f \cdot \lambda = c]$. Thus, effective power (received as well as that transmitted) as a function of frequency is another factor that tends to bias us towards higher frequencies. However, there are certain factors that bring certain limitations on the choice. The cost data shows that for antennae less than 40 feet in diameter, antenna cost is proportional to the 1.568 power of the diameter.[41] The primary reasons for such improportional increase in cost are manufacturing difficulties in shaping large parabolic structures. Antenna cost is also a function of the operational frequency because of the surface tolerance requirement ($\sim\lambda/15$) which decreases with the increasing frequency for comparable antenna efficiencies. Cost curves shown in a General Electric study[44] show that for a given antenna diameter and polarization, large-quantity antenna costs for 2.5 GHz, 8.4 GHz and 12.2 GHz are very nearly the same. However, antennae for 800 MHz operation cost more [Ref. 44, Page 4-4].

The second restriction on the antenna size at a given operational frequency is placed by the fact that with increasing antenna size (and gain), the beamwidth of the antenna decreases. The minimum beamwidth and thus the highest gain is dictated by the station-keeping characteristics of the satellite, that is, its movement in the geostationary arc in the East-West and North-South directions. If the satellite moves away from the ground receiving antenna beamwidth, the signal may be entirely lost. The antenna is required to have a large enough beamwidth or tracking capability so that despite its movements, the satellite always remains within the ground antenna's main-beam. Though current satellites have a rather large station-keeping tolerance ($\pm$ 0.5°), for future satellites in the middle and late 1970's one can safely assume

a station-keeping tolerance of $\pm$ 0.1°. At higher frequencies, this places a limit on the maximum antenna size for a low-cost small earth-terminal that does not contain any tracking capability. For 12 GHz, the maximum size for fixed-pointing antennae will be of the order of 10-12 feet assuming very rigid satellite station-keeping and 0.15° pointing error contribution from winds.

Figure 10, borrowed from Feldman's paper[38], shows the frequency dependence of Noise Temperature (or Noise Figure) of various microwave low-noise amplification and frequency conversion devices and their frequency ranges of operation. Two of the low-noise devices which could have widespread use in moderately priced earth-terminals in the future years are the Tunnel Diode amplifier and the uncooled parametric amplifier. Tunnel Diode amplifiers show little noise figure deterioration as frequency increases from 100 MHz to 20 GHz, and offer typical bandwidths of the order of 3.5-18 percent. A typical single stage small signal gain of currently available Tunnel Diode amplifiers is of the order of 12-20 dB with moderate gain variation over the band ($\pm$ 0.25 to $\pm$ 5). Typical Tunnel Diode noise figure in the frequency bands of our interest (0.8-12 GHz) is of the order of 3-7 dB. Low-noise TWT amplifiers compare rather favorably with Tunnel Diode amplifiers up to approximately 7 GHz but beyond that offer inferior noise performance. However, the advantages associated with low-noise TWT amplifiers are wide bandwidths (typically, 36-67 percent of the carrier frequency), high small signal gain (25-35 dB), and smaller gain variation over the band ($\pm$ 2 to $\pm$ 3). A major disadvantage with TWT low-noise amplifier seems to be its need for high-voltages.

Presently, uncooled parametric amplifiers are capable of operation up to 35 GHz. Their biggest advantages seem to lie in the low noise figures that they offer (typically, 1-4 dB in 1-12 GHz band). Small signal gain offered by parametric amplifiers is typically between 17-30 dB. The disadvantages associated with uncooled parametric amplifiers are poor bandwidth handling capability (typically, 0.5-7 percent) and the requirement of a pump frequency source considerably higher than the signal to be amplified (13-20 times the signal frequency for operation below 1 GHz, 4-10 times the signal frequency for operation in 1-5 GHz region, and between 1.4-4 times the signal frequency for operation beyond 5 GHz). It offers a good substitute for antenna capture area on the ground or for satellite transmitter power output but at an increased cost.

Any rigorous frequency dependence of the cost of microwave devices is difficult to establish due to the large number of variables involved. Feldman's[38,39] examination of a variety of low-noise device data suggests that when quantity effects are eliminated, price does vary with frequency of operation. Data suggest an exponent of roughly 0.3, that is $(\text{frequency})^{0.3}$. On this basis, price doubles for each decade increase in frequency. Cost of a low-noise front-end for 12 GHz would be some 1.58 times the cost of a 2.5 GHz front-end with a similar noise performance.

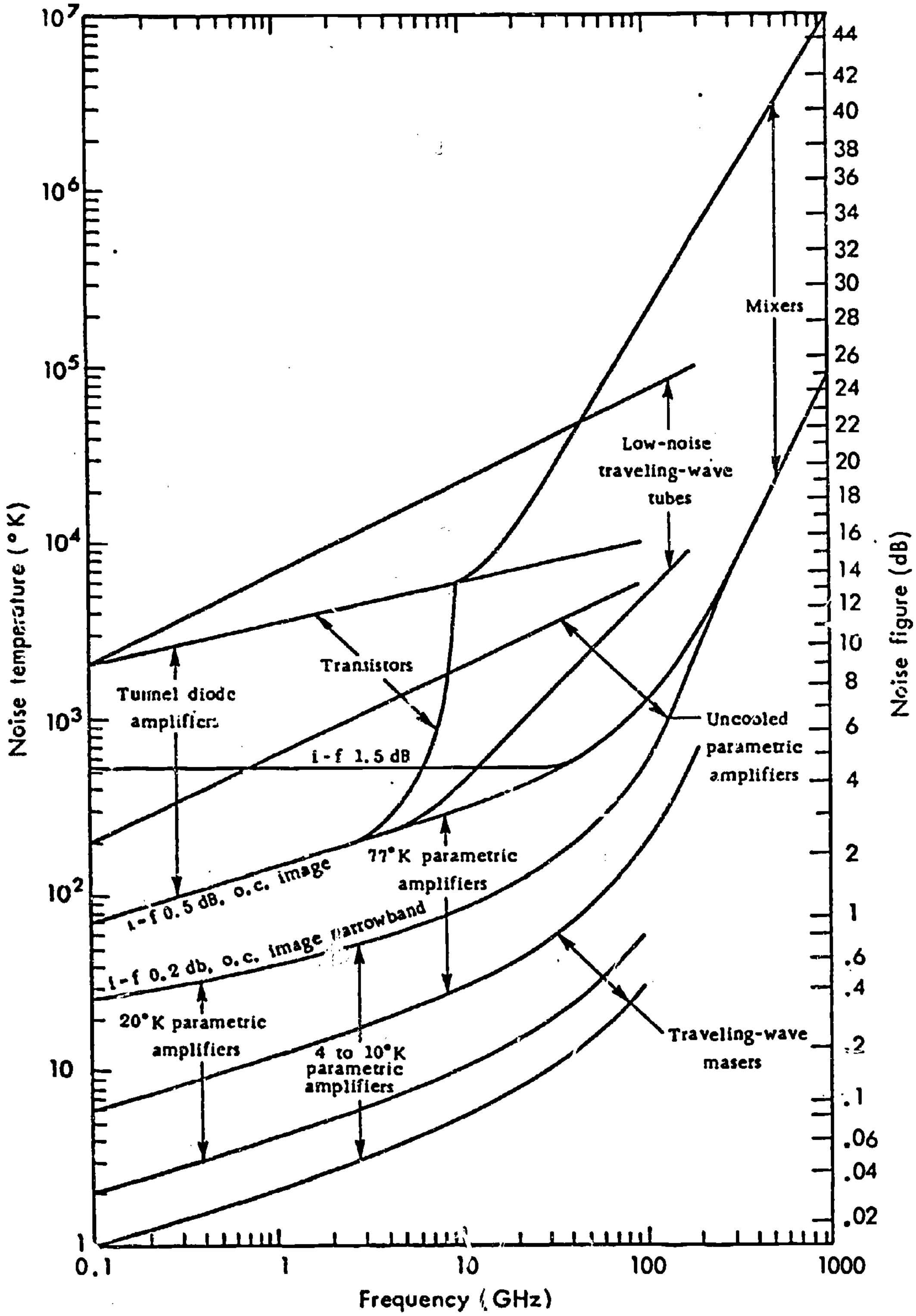


Figure 10. Comparison Of Noise-Figure And Frequency Ranges Of Low-Noise Devices [Ref. 38, 39]

A look at the currently available transmitter power output devices shows a clear degradation in the available DC power to RF power conversion efficiencies and power output as one moves to higher frequencies. Overall TWT amplifier efficiencies, including the power supply, fall from a typical value of about 25 to 35 percent at 2 GHz to about one half of that at 100 GHz. Solid-State power output devices (Gunn, IMPATT, and LSA) exhibit a poorer efficiency performance than that exhibited by either TWT or Klystron. Beyond 10 GHz, both efficiency and output power of these solid state devices suffer severe reductions. However, in spite of the low efficiencies, solid-state power output devices have many advantages as they can be joined together in a matrix or array form to obtain optimum phase and amplitude patterns. Use of modular construction increases reliability and also provides dispersion of the source of heat--a factor important from the viewpoint of spaceborne applications. In addition, the low voltage requirement of solid-state devices when compared with the kilovolt sources for tubes makes them attractive for their use in satellite transmitters.[45]

From the viewpoint of earth-station transmitter applications for earth-to-space "up" links, the main contenders are and have been TWT and Klystrons.* In certain narrow-band uplinks and single carrier per tube type of applications, "Carpitron" tubes may also find a place. Though currently available TWTs and Klystrons show decreasing efficiencies with increasing frequencies in the frequency bands of our interest (0.800 - 13 GHz), one safely can assume comparable performance for these devices over the entire band, particularly the 2.0-13.0 GHz portion of it, for the late 70's as a direct result and/or indirect spinoff from NASA's current efforts into the development of high-efficiency (>50%), broadband, and longer-life tubes with power output capabilities in the range of few hundred watts to few kilowatts.

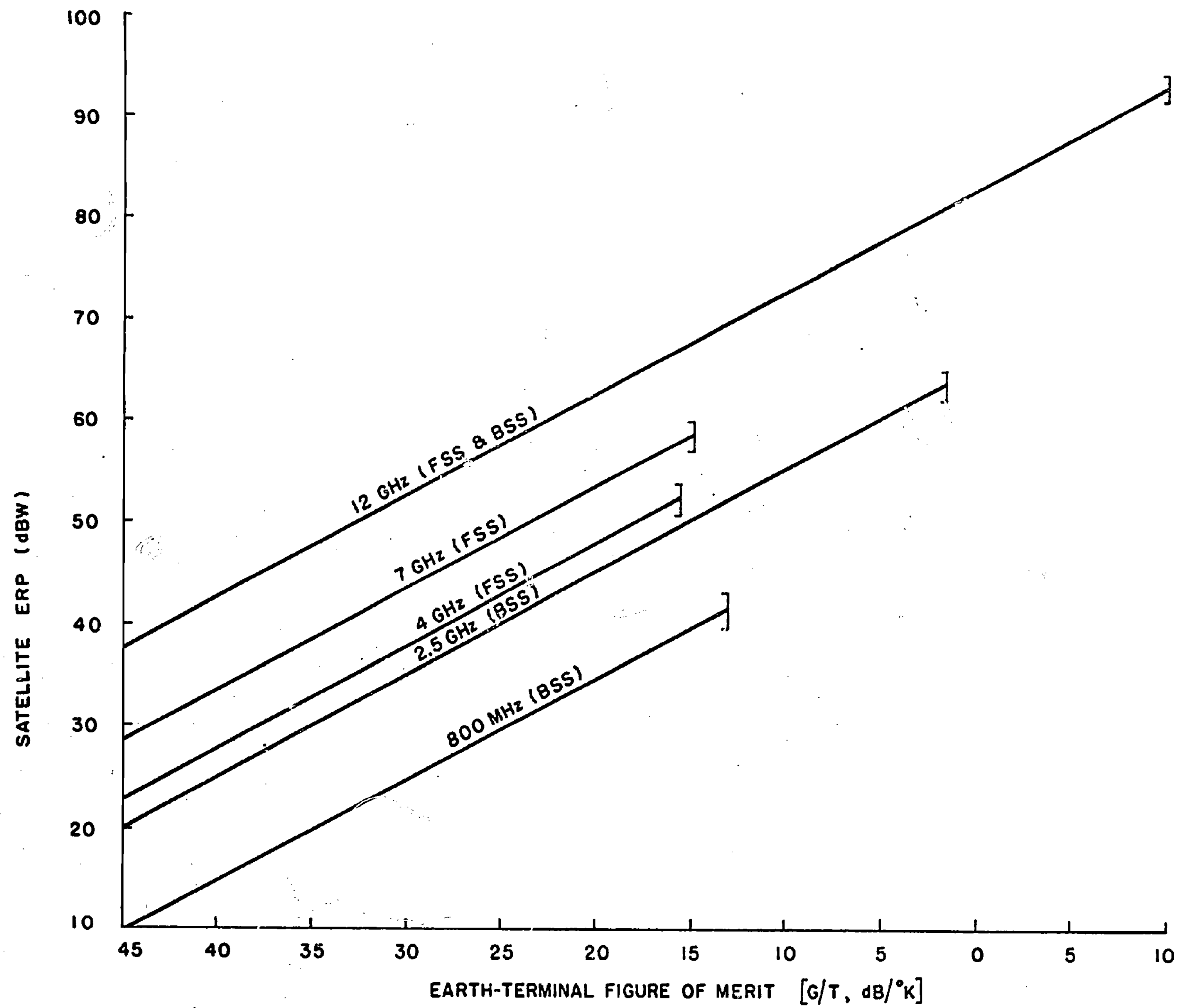
*Below 1 GHz, Gridded tubes become an important and attractive alternative.

6. INTERCONNECTION AND SPECTRUM-SPACE CONSIDERATIONS

The nature of the interconnection arrangement that is desired and the magnitude of the information to be distributed over it also influence the choice of the operational frequency band(s) for any satellite-based information networking system.

ITU frequency allocations (Section 2) clearly reflect two distinct types of satellite services: (1) Fixed-Satellite Service, previously known as Communication-Satellite Service; and (2) Broadcasting-Satellite Service. Each service has been provided with a distinct set of space-to-earth "down" link allocations with different Power-Flux Density limitations. Fixed-Satellite Service (FSS) is a service designed from the viewpoint of point-to-point communications and is also capable of wide-area TV or radio program distribution by the virtue of the high altitude of the satellite. Broadcasting-Satellite service is very much a specialized service and is designed for one-way point-to-multipoint program delivery to low-cost earth-terminals for community as well as home consumption. The distinction between Fixed-Satellite Services offering wide-area program distribution for further redistribution/rebroadcast and Broadcasting-Satellite Service offering similar capabilities is rather fine; Broadcasting-Satellite Service could deliver the program material to low-cost roof-top earth-stations whereas FSS would require relatively high-cost earth-terminals due to stricter limitations on the Power-Flux Density that it could produce on earth's surface. The final choice between the two services would be dependent upon the system requirements (the tasks that the system is required to perform), the number of points that are to be interconnected or where the program delivery is to be made, and their geographical distribution.

The relationship between satellite effective radiated power (ERP) and earth-terminal sensitivity (G/T, dB/°K) for various downlinks are plotted in Figure 11 for the reception of a single television channel. The Signal-to-Noise Ratio $[(S/N)_{p,w}]$ objective has been taken as 52 dB and is to be available at least 99.95 percent of the time. The link margins to sustain infrequent attenuations to provide this kind of link reliability have been taken as follows: (1) 0.8 GHz - 1.5 dB; (2) 2.5 GHz - 2.0 dB; (3) 4 GHz - 3.0 dB; (4) 7 GHz - 4.0 dB; and (5) 12 GHz - 8 dB. The plot also shows the maximum limit on the satellite ERPs for the various downlinks and thus the minimum earth-terminal sensitivities that could be allowed. Earth-terminal antennae elevation greater than 45° has been assumed for the calculation of the maximum ERPs. An RF bandwidth of 20 MHz has been assumed for every downlink along with the assumption that use of pre-emphasis reduces the peak-to-peak frequency deviation by a factor of 2.[6,28] For each downlink, 1.5 dB circuit losses in the spacecraft transmitter assembly is assumed. For 0.8 GHz and 2.5 GHz, use of circular-linear polarization combination is assumed to combat Faraday rotation; thus, a 3 dB polarization loss is assumed. For all downlink bands above S-band, a linear-linear polarization combination has been assumed and a polarization mismatch loss of 0.5 dB. There is no PFD limitation on 12 GHz downlink (see Section 2.2.2); hence, no maximum ERP is identified.



PERFORMANCES CALCULATED FOR A 99.95 PERCENT LINK RELIABILITY, 52 dB SNR PERFORMANCE, 20 MHz RF BANDWIDTH AND $\frac{B_{RF}}{B_V} = 4.77$

Figure 11

Our continuing studies on application of communications satellites to educational development in the United States indicate that communication satellites may have an important role in (1) Interconnecting educational institutions, particularly those related to higher education and research, for sharing of instructional, research, and administrative resources; (2) Interconnecting remote and isolated schools with certain service centers to provide students and teachers therein equitable access to services such as raw computing power, Computer-Assisted Instruction, etc. that are available to their equals in urban and suburban areas and also to provide in-service teacher development programs; and (3) Delivery of both public as well as instructional television program material for in-school as well as for in-home utilization. Figure 12 shows the basic conceptual framework for these services. One should keep in mind that the service requirements include both one-way program delivery (to some extent on on-demand basis) as well as interactive services such as computer-interconnection, multi-access computing, teleconferencing, and Computer-Assisted Instruction, which require two-way receive/transmit capability. However, the return links from the institutional headends are expected to be low-speed (up to a few tens of kilobits/second) whereas the incoming information to them would be several orders of magnitudes higher.

If all these services are to be provided through a unified system, the choice by the virtue of the accepted definitions of BSS and FSS, would have to be a Fixed-Satellite Service (FSS). Broadcasting-Satellite Service (BSS) is supposed to provide only one-way dissemination of information. However, if these services are to be accommodated on the frequencies allocated for Fixed-Satellite Services, the economic as well as political viability of these services for education interests through a unified system is in doubt. Educators would not be able to use the 2500-2690 MHz frequency band for which they put up such a gallant fight before the FCC because WARC allocated it to BSS, and would be forced to use frequencies which have severe Power-Flux density limitations or the ones that suffer from deep fades during heavy rains. This clouds the entire feasibility of a low-cost small earth-terminal satellite system concept.

One could argue that small-earth terminal operation could still be achieved by moving up to the 12 GHz band which is to be co-shared between Fixed-Satellite and Broadcasting-Satellite Services and for which WARC resolutions do not contain any PFD limitations. However, the problem at 12 GHz lies in the cost of the earth-terminals and/or satellite due to the large but localized and infrequent attenuation that frequencies in this band suffer during rains. Problems also lie in maintaining high-quality links for data-communications for a large percentage of times. Visual and aural information transmitted over the system and meant for the human consumption could tolerate increased noise levels to a larger extent during the short periods when rains are prevalent. However, degradation in noise performance beyond a certain limit would be intolerable for man-machine and machine-machine communication.

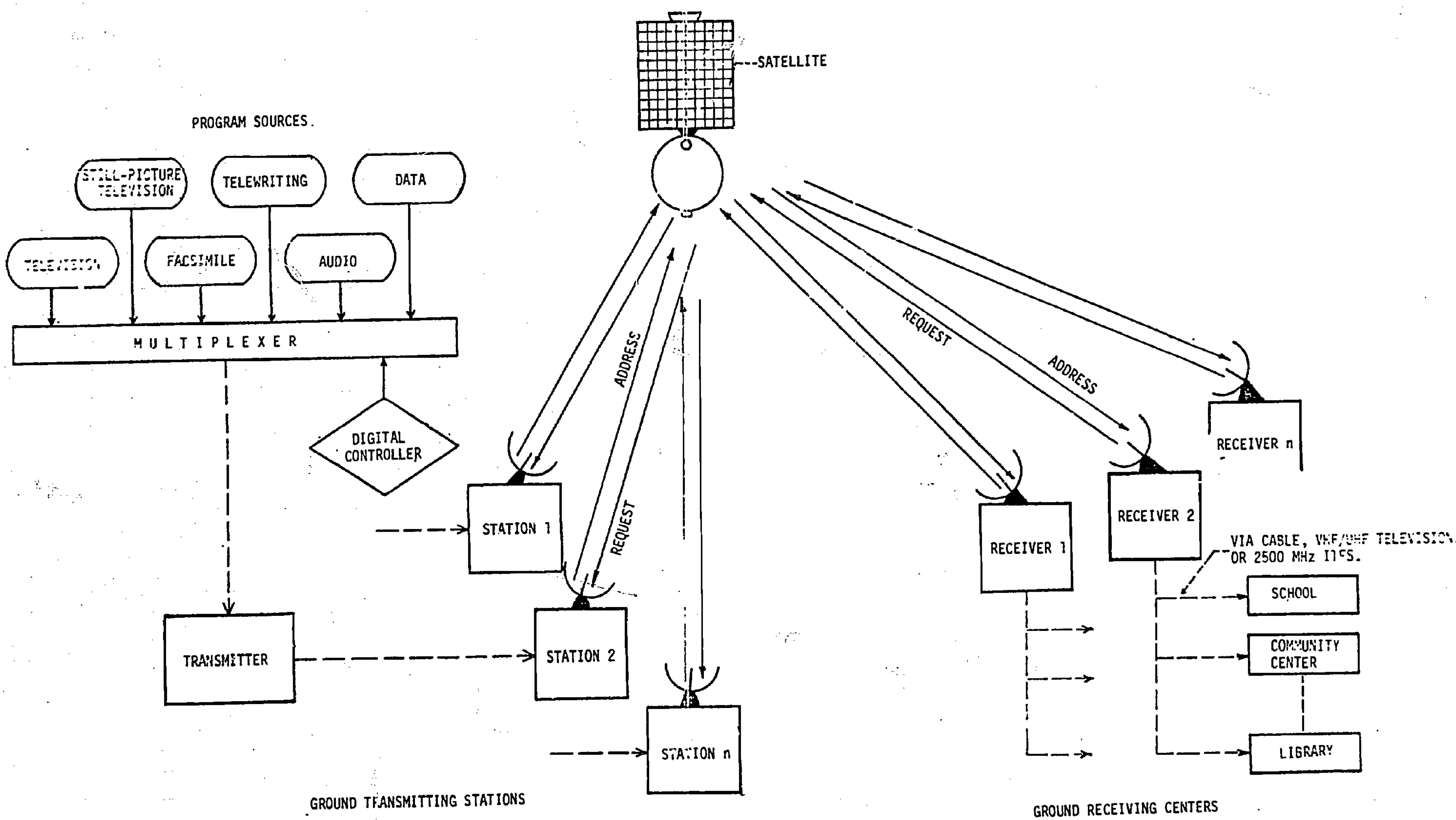


Figure 12. Educational Satellite Services

Our studies[47] have shown that it is advantageous from the viewpoint of making fullest use of the cost saving potentials of satellites to bypass the telephone company's local loop or "subscribers' plant" in delivery of telecommunications services to educational users. It is in the local plant where a large percentage of the long-distance communication costs lie. From this aspect and also from the viewpoint of avoiding the cost of any terrestrial interconnection facilities outside the "subscribers' plant", it is important that the earth-terminals for communication with satellite be located in the close proximity of the distribution/broadcasting facilities. This colocation requirement also dictates the use of 2.5 GHz and 12 GHz frequency bands (see Section 4.).

The author is of the opinion that if a meaningful educational satellite service is to be established and minimum cost communication facilities are to be provided to educational users and the public, education interests must obtain authorization from the FCC, through some sort of a national rule-making, that will permit two-way communication via relatively high-power satellites using low-cost earth-terminals in 2.5 GHz band. The final Rule and Order issued by the FCC in the matter of the preparation for WARC (Docket 18294) clearly stated FCC's intention for allocating 2500-2690 MHz frequency band for the purpose of educational and public telecommunications. It is very conceivable that the FCC could open the entire band <u>without any service restrictions</u> to educational users but still operating within the PFD limits prescribed to this band under BSS allocation. Also, to fully use the satellite-based small earth-terminal interactive potential offered by this particular frequency band (2500-2690 MHz), it is desirable to secure uplink frequency allocations in the neighborhood of S-band in addition to what is available through the WARC allocation (2655-2690 MHz uplink). One technically feasible alternative would be to divide the 2500-2690 MHz frequency band into two asymmetrical segments to provide up- and down-links and coordinate the transmission directions with DEMA allocations by choosing reverse directions. One such division could be: (1) 2500-2570 MHz educational satellite "uplink" coordinated with 2500-2535 MHz Fixed-Satellite "downlink"; and (2) 2570-2690 MHz educational satellite "downlink" coordinated with 2655-2690 MHz Fixed-Satellite uplink.

The 6 GHz uplink possibility for small earth-terminal environment could be ruled out due to a proposed rule-making that would restrict use of 6 GHz uplink transmission from antennae less than 25-30 feet in diameter. 13 GHz uplink is excessively taxing in terms of earth-station transmitter output power which has to be rather oversized to accommodate deep fades during heavy rains, that is, the transmitter has to be capable of delivering 13-16 dB more power than its normal dry-weather value during rains. In a ground-segment that consists of a large number of small receive/transmit type earth-terminals, use of 13 GHz uplink instead of one in the neighborhood of S-band would significantly raise the system cost. In addition, in a situation, where a broadband repeater processes a large number of individual carriers, a tight power co-ordination among the individual uplinks is required to maintain proper power sharing at the satellite transponder. In an S-band uplink operation, due to rain

induced, infrequent attenuation, one may entirely forget about the power coordination among the large number of carriers in a low-cost operation. However, in 13-GHz uplink operation, which suffers from localized deep fades, power coordination is a necessity and would have to be implemented through some sort of monitoring of the power level of a satellite transmitted beacon and automatic level control of transmitter power output according to the observed beacon strength. This again means a substantial increase in the earth-station cost.

Some may argue that the need for power coordination may be eliminated through the use of Time Division Multiple Access (TDMA) instead of Frequency Division Multiple Access (FDMA). However, one should recognize that TDMA requires link synchronization and would be costlier than FDMA to implement. In addition, one should remember that satellite transponders, even the channelized ones, are designed to handle at least one TV channel per output tube. This means some 30-40 MHz RF bandwidth that channelized output sections of the repeater would be required to handle. In broadband transponders, the output tube may be designed to handle the entire bandwidth at one particular allocation (for example, 190 MHz for 2500-2690 MHz band). It is inconceivable that a pure TDMA operation would be feasible even over a 30-40 MHz RF bandwidth due to the low data-rate uplinks that would be involved (few tens of kilobits/second). In all probability, even in the case of individual stations operating on TDMA basis, the satellite-borne transmitter would operate on a TDMA/FDMA basis in view of the synchronization problem that may be involved in sweeping some 1000-2000 terminals.* Thus, uplink power coordination would still be needed as at a given instance, satellite transponder would still be handling more than one signal and the signals may have suffered different localized atmospheric attenuations.

It is quite conceivable that the 2500-2690 MHz frequency band may not be wide enough to handle all educational telecommunication demands. From a single-satellite educational satellite system, one should not expect more than 4 to 5 TV channels or equivalent in one particular geographical area. The exact number of channels obtainable in one particular area would depend upon the modulation index employed and the coverage pattern of the satellite (number of beams, size of beams, etc.). It would be erroneous to assume a multi-satellite system for educational users and thus increased communication capacity from the frequency band based upon use of RF frequency interleaving, crosspolarization, satellite spacing, etc. It is conceivable that even in a single satellite operation, the communication capacity of the particular frequency band could be increased through the use of orthogonal polarization and RF frequency interleaving or staggering. However, as yet we do not know much about the depolarizing effects of rain and also the reduction in the cross-polarization isolation due to water on antenna feed and surface.

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*If each terminal had some 20 kilobit/second baseband data to be transmitted, a 40 MHz wide satellite-borne repeater could accommodate, theoretically, over 4,000 accesses (bandwidth limit) provided 4-ϕ Coherent Phase Shift Keying is used (see Ref. 47).

European Space Research Organization sponsored studies[50-52] have shown a severe drop in isolation between the cross-polarized radio channels at 11 GHz. We have no results on S-band frequencies. Use of a radome to protect the antenna feed and parabolic reflector from wetting during rains and snow is a fairly costly proposition and would have to be evaluated against the alternative of providing additional communication capacity by moving to a higher frequency, that is, 11.7-12.2 GHz frequency band. In a small-terminal environment, with terminal population in the range of few hundred to maybe ten-twenty thousand, the system cost is obviously very sensitive to any increase (or decrease) in earth-terminal costs.

If interactive communication is desired (which it certainly is) and the band is divided asymmetrically into two parts to provide for suitable uplinks, the number of channels obtainable in one particular geographical area would be further reduced. If the demand exceeds the capacity of this band, we would suggest that educational users look to the 11.7-12.2 GHz band. If the use of two different frequency bands (2.5 and 12 GHz) is deemed necessary, we would recommend that all interactive services be accommodated in 2500-2690 MHz band as far as possible, and given first preference in that band. Distribution services could be easily accommodated in the 12 GHz band because interactive services, which will primarily involve data communication would require a substantially higher link margin at 12 GHz.

We have recommended the use of 12 GHz downlink in addition to 2.5 GHz because a combination of any other downlink allocation (be it for BSS or FSS) below 12 GHz with 2.5 GHz would severely compound the co-location problem. All other downlinks (620-790 MHz, 3.7-4.2 GHz, 6.625-7.125 GHz) have a tougher Power-Flux Density limitation as well as tougher colocation problems than 2.5 GHz. In a situation, where a single satellite is carrying two different sets of transponders operating at two different frequencies and where both sets may have to be used by an individual earth-terminal, the 2.5 and 12 GHz combination seems to be the solution. If the technology would have been capable of providing low-cost adaptive or adapted arrays which could provide selective linkage with one particular set of signals while heavily discriminating against signals from other sources in the same frequency band, situation would have been different.[49] But the fact is that the technology is no where near this stage and there does not seem to be a better combination than 2.5 and 12 GHz downlinks, if the demands exceed the communication capacity of the 2.5 GHz frequency band alone.

7. CONCLUSIONS

Primary considerations in the choice of transmission frequencies for an educational satellite system are (1) ITU allocations for the Region II; (2) National rule-making that incorporates the regional allocations into domestic frequency tables, divides the allocations between government and non-government users, and, in certain cases if the situation warrants, makes certain modifications in the original allocations with the consent of the neighboring administrations; (3) Atmospheric and ionospheric frequency dependent propagation effects; (4) Man-made environment--indigenous noise as well as contributions from services and/or systems sharing the same frequency band; (5) Hardware considerations--their frequency dependent characteristics; and (6) The nature of the networking that is desired. A detailed examination of the above mentioned factors suggests that education interests should look to 2500-2690 MHz and 11.7-12.2 GHz frequency bands to meet their needs. Other allocations below 12 GHz suffer from severe power-flux density restrictions (see Figure 2) and discriminate against a low-cost, large population, small-terminal environment. They also do not lend themselves to easy colocation of the earth-terminals with terrestrial distribution/broadcast headends.

It is suggested that avenues be explored for obtaining additional frequency spectrum in the neighborhood of S-band for up-link transmissions if the interactive potentials of 2.5 GHz frequency band (down-link) are to be fully exploited. WARC allocations only allow a 35 MHz wide uplink band (2655-2690 MHz). Even this band would have to be shared with commercial operators who intend to use it for demand assigned communication in remote and isolated areas. As suggested in an earlier section, it may not be a bad idea to split up the frequency band 2500-2690 MHz asymmetrically on a 7:12 (uplink:downlink) basis and coordinate the transmission directions of the two bands with DEMA allocations by using reversed transmission directions, frequency interleaving, and orthogonal polarization. In order to initiate any exploitation of the full capabilities of the above discussed S-band allocation, it would be necessary to eliminate service restrictions on it and allocate it to satellite-based educational telecommunications to provide a variety of telecommunication services but operating within the BSS PFD limitations. The WARC allocation table shows a world-wide allocation of 2500-2690 MHz band to Broadcasting-Satellite Service. By definition, Broadcasting-Satellite Service (BSS) is a one-way service and does not include any interactive communication. If the BSS restriction is retained, the only interaction that would be permitted would be feedback or talk-back television type. Man-to-machine interaction (interactive computation, on-line information retrieval, Computer-Assisted Instruction, etc.) and machine-to-machine communication (computer interconnection) would not be permissible. From this point of view, it would be desirable for the education interests to rally for the service restriction (BSS or FSS) removal from 2500-2690 MHz band for educational applications.

If the demand for educational satellite-based telecommunication exceeds the communication capacity of the 190 MHz wide 2500-2690 MHz band, 11.7-12.2 GHz is the frequency band where additional capacity should be sought. Interactive services ought to be given preference in the 2.5 GHz band whereas the one-way distribution services could be located in 12 GHz frequency band (11.7-12.2 GHz) without much difficulty. A good portion of the interactive communication situations would deal with man-machine and machine-machine data-communication which have stiffer performance requirements in terms of a certain error rate that is to be met over a large percentage of time. Television and radio programs designed for human consumption could still be used during the deep fades period--the picture will be there though it may not be Grade 1 quality. To sustain high quality data-links at 12 GHz would require over-sized satellite transmitter power and/or highly increased earth-terminal sensitivities than those required for normal dry-weather operation. This will certainly raise the system cost substantially.

WARC has allocated the frequency band 11.7-12.2 GHz on a co-equal basis between Broadcasting-Satellite and Fixed-Satellite Services. Much of the exploitation of the great potentials of this band for delivering program material in a low-cost, large population, small earth-terminal environment would depend upon how the use of this band is initiated in the beginning. It is clear that relatively low- or moderately-powered satellites would be the ones that would move into this band first; that is, fixed-satellite service would be first to enter into this band. If Fixed-Satellite services are allowed to develop in the entire band, the possibility for a future introduction of a high-power satellite(s) would diminish due to the protection requirements inherent in co-equal sharing. Under co-equal sharing, the services that come first in the band are to be protected against intolerable interference from future systems. Possibly, the early introduction of Fixed-Satellites in the entire 12 GHz band would have the effect of closing the doors to BSS in this band. It becomes necessary to develop certain mechanisms to protect future services too (and particularly the high-power satellite systems) and not to rely solely on COMSAT's evolutionary concept (see Appendix A). A solution would be to evenly divide the 11.7-12.2 GHz frequency band with the first half having BSS as a primary service and FSS as a secondary service, and the second half with FSS designated as the primary service and BSS a secondary service.

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